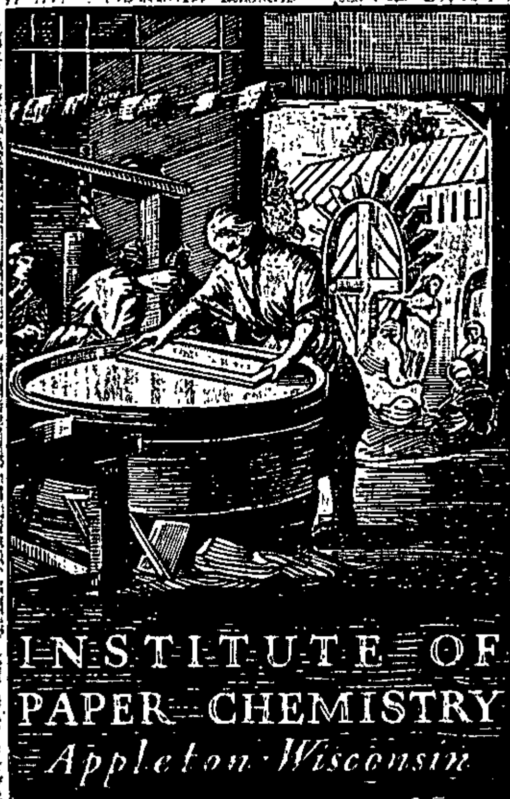

CONFIDENTIAL

SELECTIVE DELIGNIFICATION OF WOOD AND OTHER FIBROUS MATERIALS

AN ECONOMIC ANALYSIS

Project 2500

Report Twenty
A Progress Report
to
THE GRANTORS

July 5, 1973

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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SUMMARY

An analysis of holopulp economics compared to conventional processes has been carried out. This analysis considered pulp production, papermaking, and environmental aspects. It was found that, in general, holopulping is a more expensive process than kraft. Pulp production costs (excluding capital) are likely to be $5 to $10/ton pulp higher and capital requirements for a new plant would run $10,000 to $15,000/daily ton higher. It appears unlikely, under present circumstances, that these costs can be entirely justified by savings in papermaking or environmental areas.

Production economics hinge on a simple trade-off between reduced wood costs and increased chemical costs. Under present conditions, the savings in wood cost cannot match the higher chemical costs. The high chemical costs are directly related to the use of electrolytic steps in the holopulp process, and are thus associated with the use of ClO_2 and Cl_2 as pulping chemicals. These costs are essentially unavoidable so long as these chemicals are used.

Consideration was given to possible economic advantages in the paper-making area. The ease of refining could result in cost savings of $2 to $3/ton. Other possible advantages, such as better runnability, lack a sufficient data base to draw meaningful conclusions.

The most significant advantage in the environmental area is the elimination of the malodorous TRS emissions. This could result in cost savings of about

\$2/ADT which could become much greater if restrictions on kraft odor get tighter. The favorable air emission picture is tarnished somewhat by potential water pollution problems with evaporator condensates and unrecovered liquor.

Internal process variables have only a minor influence on the economics. No major breakthrough in holopulp costs is likely to come through manipulation of process variables. Only major changes in pulping stoichiometry to reduce usage of ClO_2 and other chlorine chemicals can significantly reduce costs. This would require either the use of a less expensive delignifying agent, or the production of high residual lignin pulps.

The future economic outlook for holopulping depends mainly on the relative costs of wood *versus* fuels and electrical energy, and the shape of environmental restrictions. The present "energy crisis" is not a favorable development.

INTRODUCTION.

The work on holopulping over the last eighteen months was intended to bring Project 2500 to a logical conclusion by emphasizing those areas having the most significant effect on the overall technical and economic feasibility. The overall objective was to bring the work on holopulp to a point where a reasonable assessment of the potential of holopulping could be made. This was to include an economic evaluation of the process encompassing economic and quality factors of pulp utilization, and a demonstration of technical soundness for those key steps furthest removed from present technology. This report is concerned with the economic evaluation.

The objectives of this report are as follows:

1. Describe the process and process alternatives in sufficient detail to provide a base for economic evaluation.
2. Define all of the major cost items and provide a means for estimating each of these costs.
3. Define the cost elements which are subject to significant variation and estimate the limits of this variation.
4. Compare holopulping economics with the economics of existing processes.
5. Assess the economic outlook of holopulping.

The analysis is carried out on a differential basis to permit a direct comparison of the costs of holopulping with the costs of other processes. In this method, the emphasis is on cost differences between processes. The analysis is formulated in a general manner so that any well-defined pulp can be used as a reference. However, kraft is used as a reference in this report when specific examples are needed.

The economic analysis is divided into three parts: pulp production, papermaking and environmental. The first is concerned with the costs of producing a unit weight of pulp and is basic to the whole analysis. The second part examines the use of holopulp in papermaking and the economic implications of the particular properties of holopulps. The third part is concerned with the environmental aspects of the processes and how this will affect the cost picture.

Although the analysis is formulated in a general sense, detailed cost estimates are provided for a few selected cases. These are chosen to fit with the work which has been done on pulping.

PROCESS DESCRIPTION

For the purpose of this analysis, the holopulping process can be defined as a pulping process which employs thermomechanical defibration of wood chips along with sequential steps involving the use of caustic and oxidative treatments based mainly on the use of chlorine dioxide, chlorine and hypochlorite; combined with a recovery process for treating the waste liquors generated in the pulping process. The pulping process itself is sulfur-free as is the closed recovery process. If the recovery process is operated in open loop or partially open loop fashion, sulfuric acid could be used for generating chlorine dioxide. Otherwise, the holopulping process employs only chemicals based on the elements sodium and chlorine.

The pulping step may include a wide variety of individual operations consisting of various combinations of defibration, oxidation, and alkaline extraction steps. Among the variables are number of stages, proportions of chemical applied in any given stage, total amounts of chemicals used, and possible chemical treatments before the defibration stage. In addition, the extent of washing between stages, the degree of liquor recycle within the pulping operation itself, and the possible application of chemicals in the gas phase are potential variations.

The recovery process must handle the spent liquor, containing sodium and chlorine produced by the pulping operation. Upon concentration and incineration, the sodium and chlorine are recovered as $NaCl$, Na_2CO_3 and HCl depending on the proportions of sodium and chlorine in the liquor. These recovered chemicals can then be processed and recycled to the pulping process. The exact configuration of the recovery system is dependent on the relative amounts of sodium and chlorine in the spent liquor and on the degree of closure of the recovery system. Three major alternatives can be distinguished:

1. Sodium chloride is the predominant recovered chemical and all of the caustic is produced electrochemically.
2. Sodium carbonate is the predominant recovered chemical and the bulk of the caustic is produced by causticizing with lime.
3. There is only waste treatment of the liquor and no recovery.

Schematic flow diagrams for each of these systems are shown in Fig. 1, 2, and 3.

Since the economic analysis is to be applied to several different process variations rather than to a specific flow sheet, it is necessary to focus attention on those variables having the greatest influence on the economics. This eliminates the need for detailed flow sheets on each alternative considered. With respect to the pulping operation itself, the major factors influencing the economics are pulp yield, the total amounts of

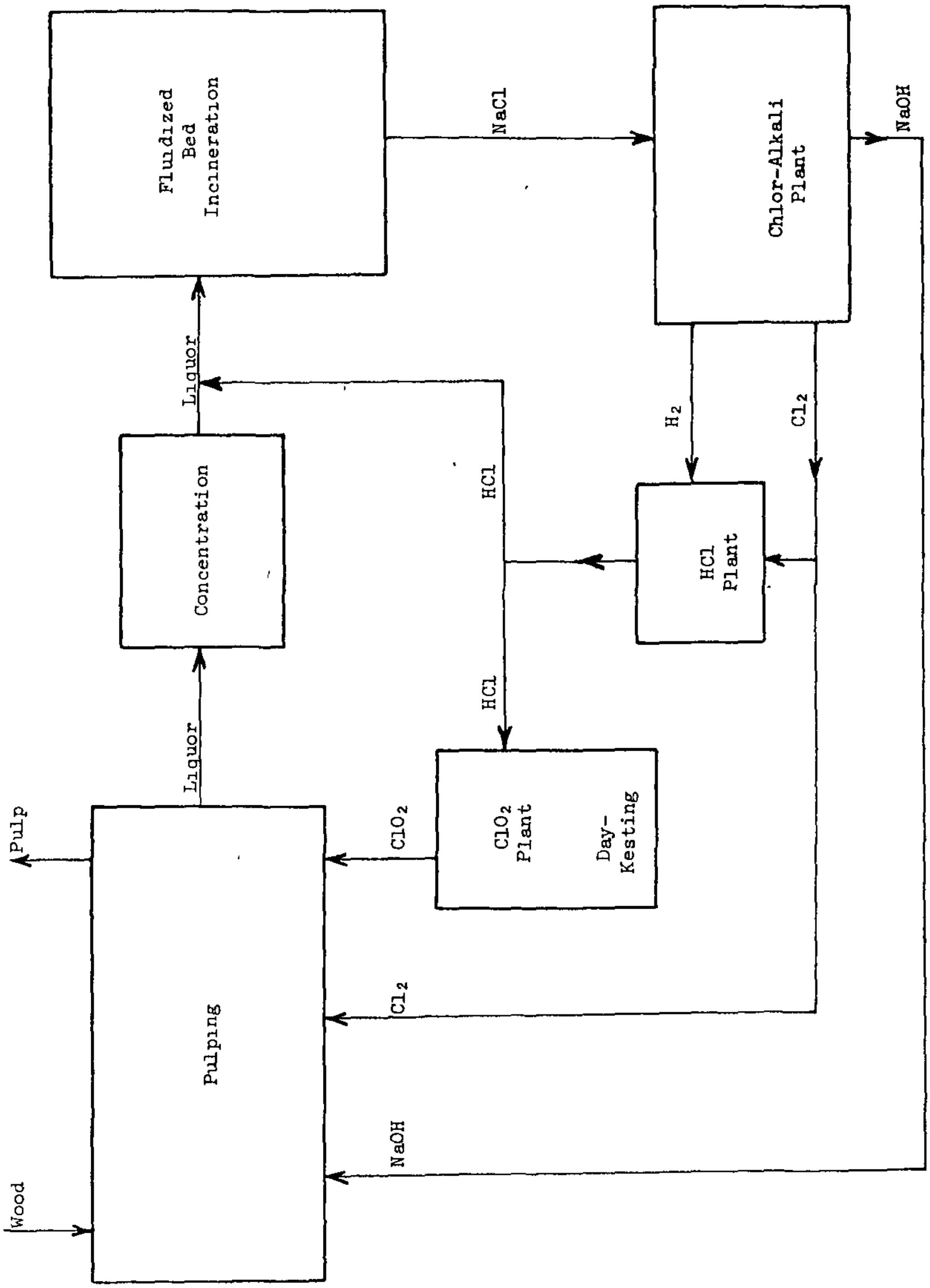

Figure 1. Schematic Diagram of "All-Electrolytic" Holopulp Process

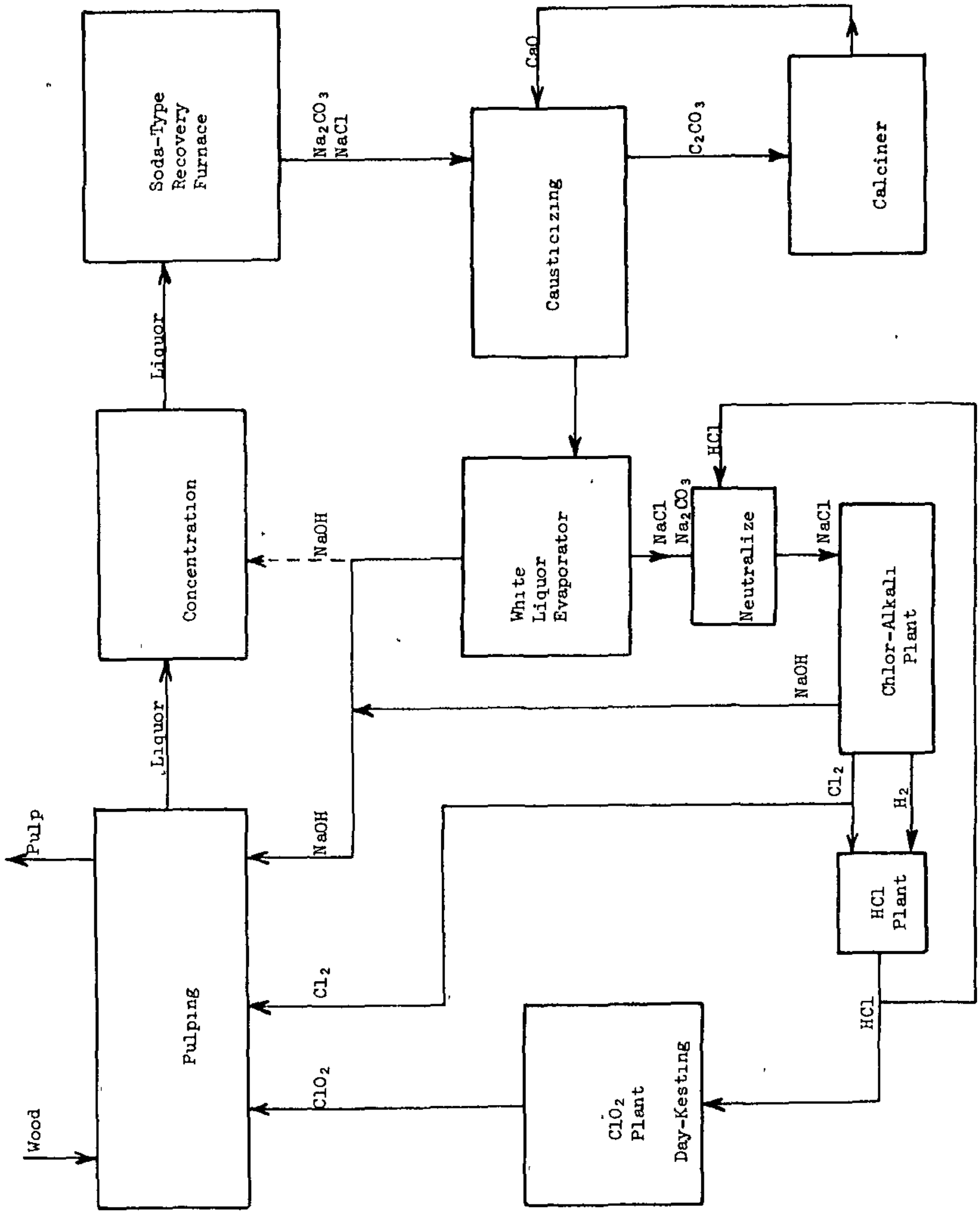

Figure 2. Schematic Diagram of Holopulp Process Employing Causticizing

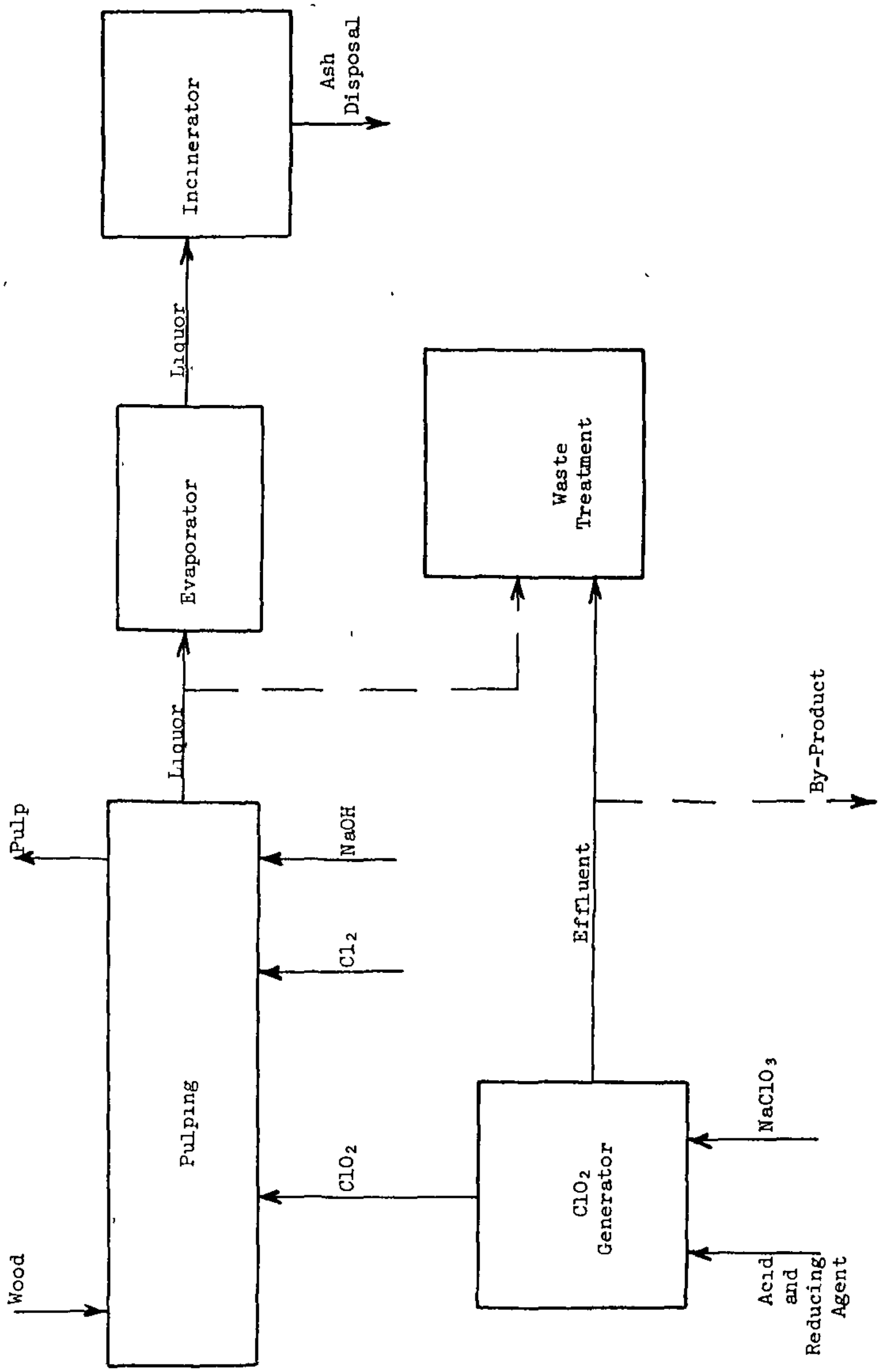

Figure 3. Schematic Diagram of Holopulp Process Without Recovery

each chemical used, the concentration of spent liquor produced, and the effect of the number of pulping and washing stages on the capital required. In the recovery system, the major factors are the amounts of liquor solids, fractions of sodium and chlorine, and the recovery system configuration. The analysis is simplified if the recovery costs can be translated directly to the major variables in the pulping operation. Thus, recovery costs should be allocated to chemical costs to as large an extent as possible. In this manner, the effects of process variations on overall costs will be most clearly evident.

PULP PRODUCTION COSTS

The starting point in the economic evaluation of holopulping is a determination of the costs of producing a unit weight (e.g., an airdry ton) of holopulp for comparison with the costs of producing pulp by other processes. The following cost elements are considered in this analysis:

1. Wood costs
2. Chemical and utilities costs
3. Capital requirements
4. Labor costs
5. By-products

Although this breakdown would be sufficient for comparing costs with some reference process, it is helpful to separate some of these factors to determine the effective cost of recycled chemicals. This permits rapid evaluation of the effects of changes in pulping stoichiometry on pulp production costs. This technique is used in part of this analysis.

WOOD COSTS

Wood is the basic raw material for nearly all pulping processes and the cost of wood is a very important part of the overall economics of pulping. One of the major advantages anticipated with holopulping is a savings in wood costs due to the higher yield. The higher yields characteristic of holopulp are a consequence of the more selective delignification, and reduce the amount of wood required to produce a given weight of pulp. The reduction in wood costs due to higher yields is the greatest single plus factor in holopulp economics.

Increased yields have an economic impact beyond the obvious reduction in the amount of raw wood that has to be purchased. The reduction in the amount of wood needed to produce a given weight of pulp means a corresponding reduction in the size of the woodyard and wood preparation facilities required. This will result in a decrease in the capital costs for these items and could also result in some reductions in labor and utilities costs for this part of the system.

Savings in wood costs can be analyzed quantitatively in the following manner. A reference pulp is chosen which could be a pulp produced by any well-defined process. Each individual cost item is then quantified and the difference between the cost of that item for the reference pulp and for holopulp represents a "savings" for holopulp. The sum of these items is the net savings in wood costs to the holopulping process. The individual items considered are raw wood costs, capital investment in wood handling facilities, and utility and labor costs in wood preparation. All costs are referenced to one airdry ton of pulp (ADT).

The net savings to the holopulping process can be written as follows:

$$\begin{aligned} \text{Savings} = {} & C_W \left(\frac{1}{f_R Y_R} - \frac{1}{f_H Y_H}\right) + \frac{rI_R}{P}\left[1 - \left(\frac{f_R Y_R}{f_H Y_H}\right)^n\right] \\ & + C_U \left(\frac{1}{f_R Y_R} - \frac{1}{f_H Y_H}\right) + C_L \left[1 - \left(\frac{f_R Y_R}{f_H Y_H}\right)^{n_L}\right] \end{aligned} \tag{1}$$

where: C_W = unit cost of raw wood, \$/ADT wood

f = fraction of raw wood remaining after barking, chipping and other processing steps

Y = pulp yield, lb. pulp/lb. wood cooked

R,H = subscripts denoting reference pulp and holopulp, respectively

I_R = total capital investment in wood preparation facilities for reference pulp

P = annual pulp production rate

r = annual charge factor against capital

n = scale-up factor for wood handling

C_U = unit cost of utilities used in wood preparation, \$/ADT wood

C_L = unit cost of labor for wood handling for reference pulp, \$/ADT pulp

n_L = scale factor for labor

This analysis assumes that the comparison is between pulps utilizing the same wood supply so that only one unit cost for raw wood is needed. The fraction, f, is included in the analysis to allow for the possibility that different processes may require different degrees of cleanliness in the chips prior to pulping and, hence, different barking losses. It is assumed that the investment in wood preparation facilities is related to size according to a power law expression. The amounts of the various utilities charged against wood preparation are expected to be proportional to the amount of wood handled. It is assumed that a power law expression can be used to account for the effect of size on labor costs. Peters and Timmerhaus (1) suggest an exponent of 0.2 to 0.25 for this purpose.

Equation (1) can be rearranged slightly to give:

$$\text{Savings} = \frac{(C_W + C_U)}{f_R Y_R}\left(1 - \frac{f_R Y_R}{f_H Y_H}\right) + \frac{rI_R}{P}\left[1 - \left(\frac{f_R Y_R}{f_H Y_H}\right)^n\right] + C_L\left[1 - \left(\frac{f_R Y_R}{f_H Y_H}\right)^{n_L}\right] \quad (2)$$

In interpreting Equation (2), it should be noted that the terms $\frac{C_W}{f_R Y_R}$, $\frac{C_U}{f_R Y_R}$, $\frac{rI_R}{P}$, and C_L are the costs per ADT of reference pulp for raw wood, utilities, investment and labor, respectively. The sum of these four terms is the total wood cost for the reference pulp per ADT, C_{WR}. Thus:

$$C_{WR} = \frac{C_W}{f_R Y_R} + \frac{C_U}{f_R Y_R} + \frac{rI_R}{P} + C_L. \quad (3)$$

Equation (2) can be expressed in terms of this cost factor as follows:

$$\text{Savings} = C_{WR}\left(1 - \frac{f_R Y_R}{f_H Y_H}\right) - \frac{rI_R}{P}\left(\frac{f_R Y_R}{f_H Y_H}\right)\left[\left(\frac{f_H Y_H}{f_R Y_R}\right)^{1-n} - 1\right] - C_L\left(\frac{f_R Y_R}{f_H Y_H}\right)\left[\left(\frac{f_H Y_H}{f_R Y_R}\right)^{1-n_L} - 1\right]. \quad (4)$$

It may be noted that the net savings on wood for holopulping is less than would be predicted simply by the cost of wood for the reference pulp and the yield ratio [the first term in Equation (4)].

An alternative way of looking at the savings in wood costs is to consider the unit cost of clean wood for each process. Thus:

$$\text{Savings} = \frac{C_{CWR}}{f_R Y_R} - \frac{C_{CWH}}{f_H Y_H} = \frac{C_{CWR}}{f_R Y_R}\ 1 - \frac{f_R Y_R}{f_H Y_H} - \frac{\Delta C}{f_H Y_H}. \quad (5)$$

where:

C_{CWR} = unit cost of clean wood for reference pulp, \$/ADT wood

C_{CWH} = unit cost of clean wood for holopulp, \$/ADT wood

ΔC = $C_{CWH} - C_{CWR}$, difference in unit cost of clean wood between holopulp and reference pulp.

By comparing Equation (5) with Equation (4), it is seen that:

$$\Delta C = \frac{rI_R}{P} \; f_R Y_R \left[\left(\frac{f_H Y_H}{f_R Y_R} \right)^{1-n} - 1 \right] - C_L f_R Y_R \left[\left(\frac{f_H Y_H}{f_R Y_R} \right)^{1-n_L} - 1 \right] . \qquad (6)$$

This difference in the unit cost of clean wood between holopulp and the reference pulp is a consequence of the economy of scale. The larger capacity plant required for the lower yield reference pulp means a somewhat lower cost for capital and labor per unit weight of wood processed. These differences are neglected when it is assumed that costs for clean wood are the same within the two processes.

The above equations are rather complex and require a great deal of information which is difficult to obtain. The simplest estimation of the savings in wood cost is obtained by neglecting the differences in wood processing costs and by assuming f_R equals f_H (no difference in cleanliness requirements). Then:

$$\text{Savings} = C_{WR} \left(1 - \frac{Y_R}{Y_H} \right). \qquad (7)$$

This estimation is favorable for holopulp (gives the benefit of the doubt to holopulp), since the terms which are neglected would tend to reduce the savings in wood costs for holopulp. Savings estimated according to Equation (7) are shown graphically in Fig. 4 and 5.

Figure 4 shows the savings in wood costs as a function of holopulp yield at different values of reference pulp yield and reference wood costs. Figure 5 shows the relationship between holopulp yield and the wood cost for the reference pulp to give savings of \$10 and \$15 per ADT at two different values of the reference pulp yield. These curves and/or Equation (7) can be

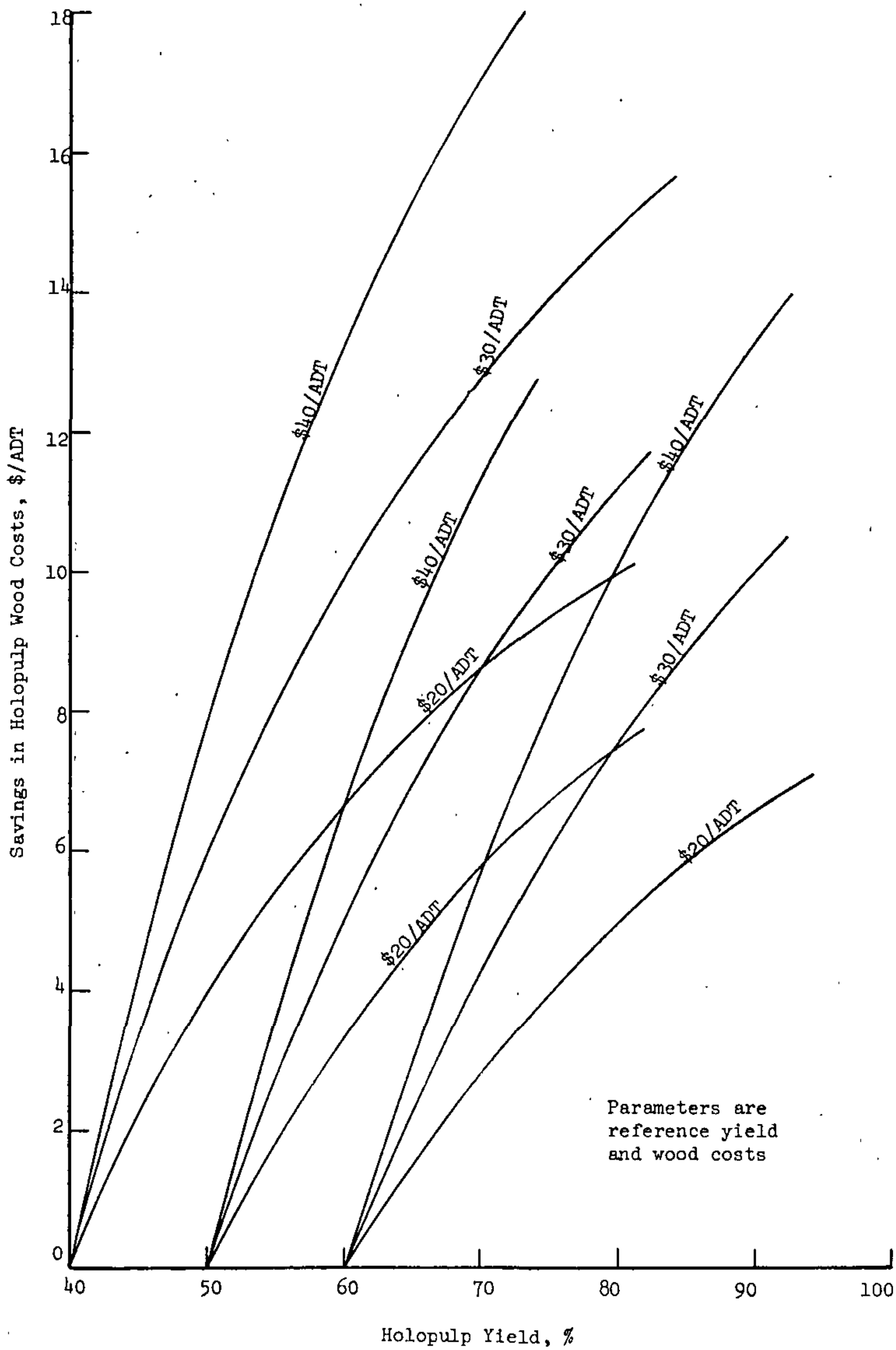

Figure 4. Savings in Wood Costs for Holopulp

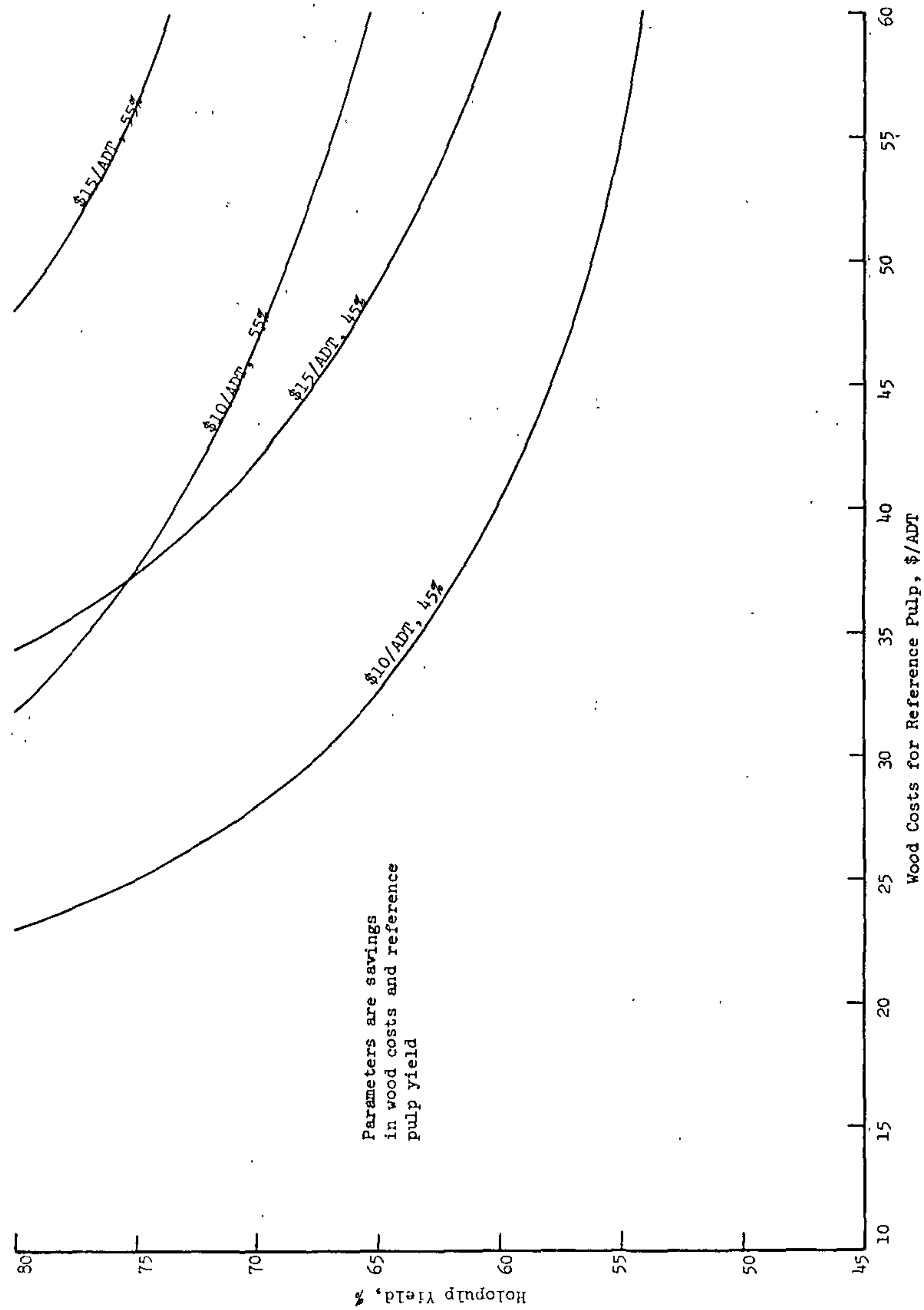

Figure 5. Holopulp Yields Required to Generate Specific Savings in Wood Costs

used to determine the savings in wood costs will run less than \$10/ADT. Only when wood costs for the reference pulp exceed \$40/ADT is it likely that savings in wood costs for holopulp will exceed \$10/ADT. This prediction would appear to be conservative, since the assumptions in arriving at Equation (7) were such as to overestimate the savings in holopulp costs. This is not to denigrate savings of \$10/ADT. However, this value must be kept in mind in looking at other aspects of the economic picture where holopulp costs will be greater. The savings in wood costs are highly dependent on the cost of wood for the reference process. When these costs exceed \$50/ADT, very significant savings are possible.

CHEMICAL AND UTILITY COSTS

Although wood probably constitutes the largest single item in pulp costs, cost of chemicals and utilities are a major part of the direct operating expense. When the processes under consideration include a chemical recovery system, there are two alternatives in estimating chemical and utility costs:

1. Costs can be assigned for all chemicals used in pulping and for those utilities used in the pulping step. Capital and operating costs for the recovery system are used to determine unit costs for the recovered chemicals.
2. Chemical costs are assigned only for make-up chemicals and charges made for all utilities used in both the pulping and the recovery system. Capital requirements are then handled on a totally separate basis.

There are advantages and disadvantages to either of these approaches. The first approach is much more suitable for quick estimates of these costs and for examining the effects of pulping stoichiometry variations on overall costs. Current market prices can be used as a guide in assigning unit costs for chemicals. The second approach provides a clearer appreciation for the source of costs and the potential for variability. However, it is a much more unwieldy approach and is less suitable for examining the effects of pulping stoichiometry variations on overall costs. Both of these methods are used in this report to get a better perspective on the cost picture.

FIRST APPROACH

The chemicals used in holopulping may be considered to be chlorine dioxide (ClO_2), chlorine (Cl_2), and caustic (NaOH). In addition to the costs of these chemicals, charges for the electrical power used in the fiberizing step and for steam used in fiberizing and heating to reaction temperatures should be made. Charges to be applied to the reference pulp will depend on the process. They would include chemical, electrical, and steam costs. If the reference pulp is not semichemical, electrical power costs could be neglected and the steam required would be that for heating the digesters. Bleaching costs can be considered in a similar manner.

The costs for chemicals and utilities for either holopulp or the reference pulp are determined as the sum of products of the amounts of each item per unit weight of pulp and the unit costs of these items. When a chemical recovery system is involved, the unit costs for chemicals, steam, and electrical power are not necessarily the same for holopulp and the reference pulp. Estimates of chemicals and utilities costs for holopulp and for kraft as a reference are provided below.

Holopulp Costs

Chlorine Dioxide

This chemical is primarily responsible for selective delignification and amounts used have varied from about 4 to 10% based on the wood. Reductions in the amount of ClO_2 used are accompanied by a corresponding reduction in delignification leading to higher yields and K numbers. If a similar degree of delignification is to be reached at lower ClO_2 consumptions, more delignification must be obtained from the NaOH in a less selective manner. This would result in greater caustic consumptions and lower overall yields. To a certain extent, ClO_2 consumption can be reduced by replacing it with chlorine. This retains more of the selectivity of delignification. Although pulps can be produced over the range of 4 to 10% ClO_2 consumption, the characteristics of the pulps vary widely. If a bleachable grade of pulp is required, the ClO_2 consumption would have to exceed 6% for hardwoods and significantly more for softwoods. With a full-blown recovery system and favorable scale and power costs, the unit cost of ClO_2 would be about 10 cents/lb. ± 2 cents/lb. Thus, the total cost of ClO_2 per ton of pulp would be expected to range from $8 to $32, with the most likely value about $20 per ton. Under most circumstances, the cost of ClO_2 would exceed savings in wood costs. The cost of chlorine dioxide is such a dominant factor in holopulp economics that it is desirable to relate it quantitatively to the major variables. These relationships are shown graphically in Fig. 6 based on the following cost equation:

$$ClO_2 \text{ cost} = \frac{0.18\, S_D C_D}{Y} \qquad (8)$$

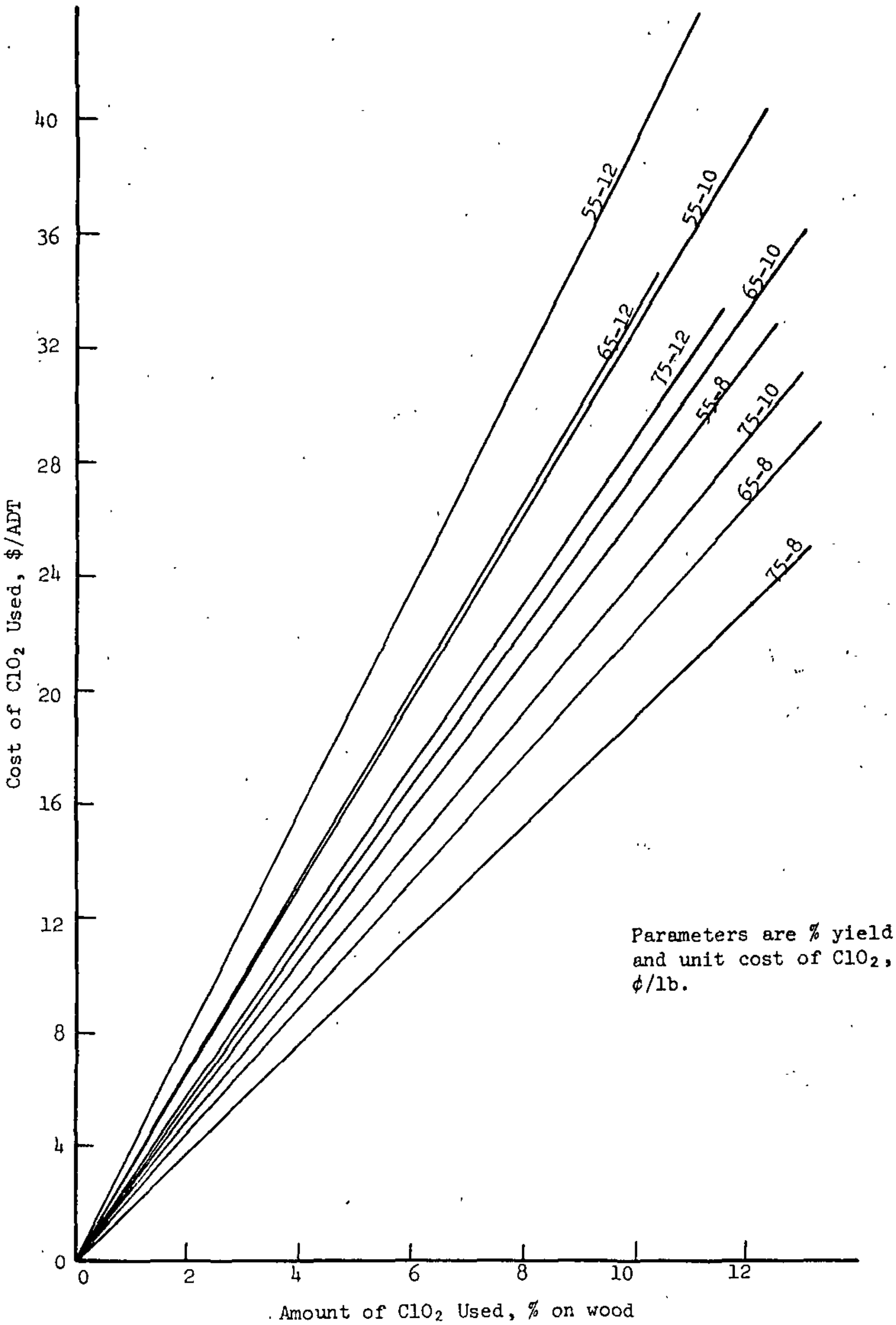

Figure 6. Costs of Using ClO_2 as a Pulping Agent

where $\underline{S_D}$ = ClO_2 consumed, % on wood

$\underline{C_D}$ = unit cost of ClO_2, cents/lb.

$\underline{Y}$ = holopulp yield, lb. pulp/lb. wood.

Chlorine

This chemical is another oxidant which is less selective and less effective per unit weight than ClO_2. Chlorine has not been considered a prime delignificant in holopulping, but because of the lower cost of chlorine, work has been directed at using chlorine to substitute for some of the ClO_2. Chlorine usages as high as 14% on the wood have been examined with up to 80% of the total oxidant demand satisfied with chlorine. The current f.o.b. price listed for papermakers chlorine in the Oil Paint and Drug Reporter (2) is 3.75 cents/lb. Thus, costs for chlorine could range up to $14/ADT of pulp. However, with a recovery system, the unit cost for chlorine would probably range from 2 to 3 cents/lb. and the cost for chlorine would be less than $10/ADT. If it is assumed that Cl_2 can replace ClO_2 in the ratio of oxidizing equivalents (2.63 lb. Cl_2 = 1 lb. ClO_2) and using costs of 3 cents/lb. for Cl_2 and 10 cents/lb. for ClO_2, each % of chlorine used would reduce costs by 22 cents/ADT for a 65% yield holopulp. Savings in chemical costs on substituting chlorine for ClO_2 are very sensitive to the unit costs of the two chemicals. This is shown in Fig. 7. The situation is actually more complex than is indicated by Fig. 7. Increased use of chlorine tends to generate more acids and thus the amount of NaOH required for the extraction step. In addition, use of chlorine to replace part of the ClO_2 will change the proportions of chlorine and sodium in the spent liquor, which could effect the recovery flow sheet and the unit costs of Cl_2, ClO_2, and NaOH.

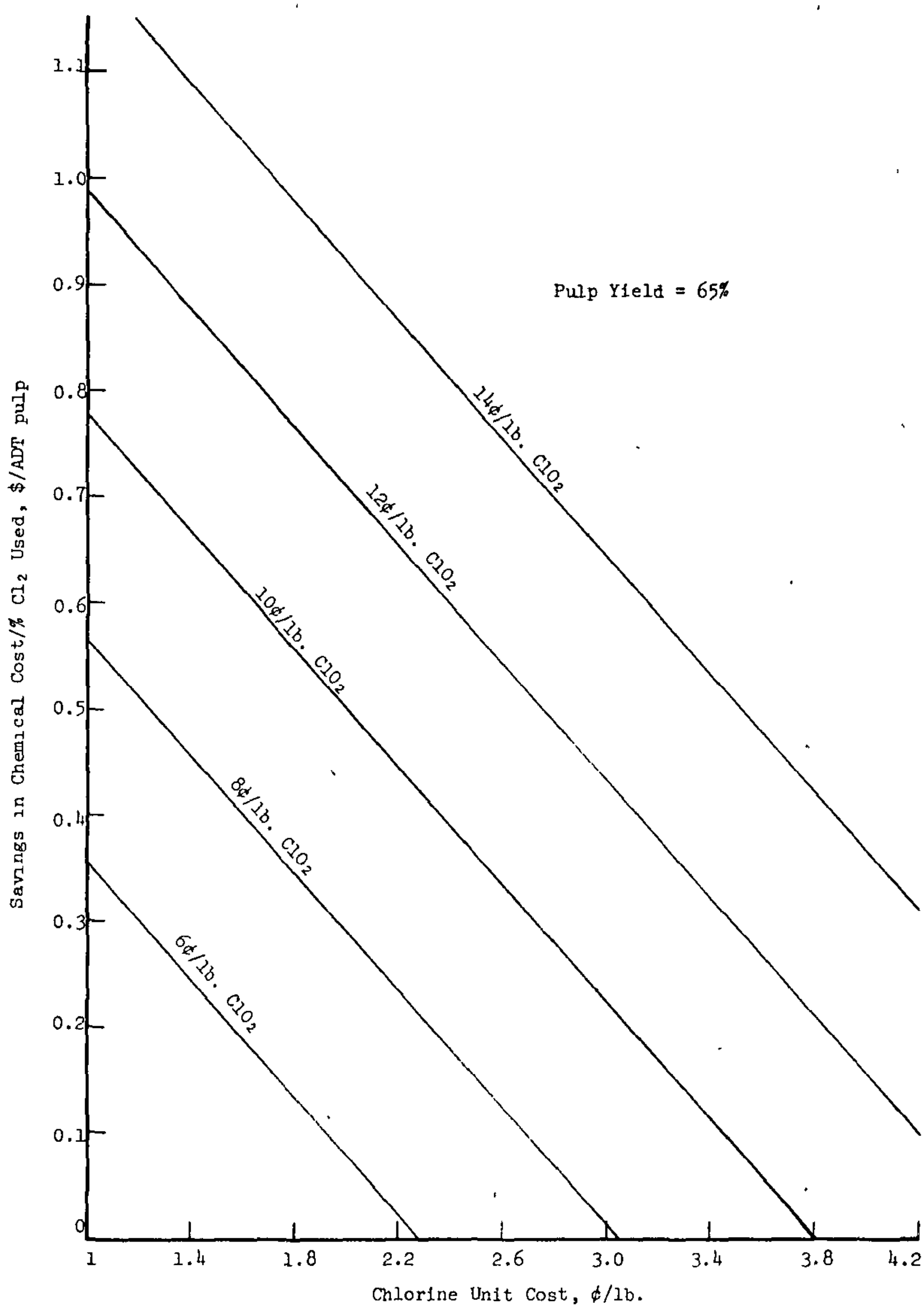

Figure 7. Cost Savings on Substituting Cl_2 for ClO_2

Caustic

Caustic is used in extraction steps which follow oxidative treatments. It may also be used in alkaline pretreatments prior to any oxidation. Selective delignification as practiced in the holopulping process is actually a two-step operation. The oxidation changes the lignin so as to render it soluble in alkaline solution. A part of the caustic used reacts with the oxidized lignin and a part neutralizes some of the acids formed in the oxidation step. In addition, caustic can take part in nonselective delignification reactions. Amounts of caustic used in these studies have ranged up to 12% on the wood with hardwoods, and 15% for softwoods. The current market price is listed at 3.8 cents/lb., but with a recovery system, it appears that the unit cost for caustic would run from 2 to 3 cents/lb. Hence, costs for NaOH are expected to range from $4 to $12 per airdry ton pulp with a most probable value of about $6 to $7/ADT. This cost could be highly sensitive to the Cl/Na ratio in the spent liquor, since this determines the amount of electrolytic caustic that must be made.

Electrical Power

The main requirement for electrical power in the pulping step, besides the usual for pumps, etc., is for fiberizing the chips. Recent tests with a double-disk refiner have shown that the power required for this purpose is under 5 horsepower days per ton of wood processed for both hardwoods and softwoods. This would lead to a power requirement for fiberizing of about 130 kw.-hr./ADT pulp. If power unit costs are assumed to range from 0.8 cents to 1.2 cents per kw.-hr., this cost would run about $1 to $1.5 per ADT pulp. This cost is quite low relative to other costs.

Steam

Steam is required both for fiberizing and for heating the reaction vessels to the desired temperature. In Progress Report Eleven (3), this was estimated to be about 1500 lb./ADT pulp. If steam costs are taken to range from 50 cents to $1 per 1000 lb. steam, the costs per ton of pulp would be about $1 to $2. This cost is also small relative to the chemical costs.

Summary

The total cost of chemicals and utilities for holopulping would be on the order of $28/ADT pulp and might range from $20 to $40/ADT. The major contributor to this cost is the cost of ClO_2 which dominates the cost picture. For proximate analyses of costs, the assumption of 10 cents/lb. for ClO_2 and 2.5 cents/lb. for Cl_2 and NaOH appears quite reasonable.

Kraft Costs

In order to interpret the significance of these costs for holopulp, it is necessary to look at the same costs for a reference pulp. As the dominant pulping process in the industry today, kraft is the logical reference process. The difference between the costs for chemicals and utilities between holopulp and kraft may then be compared with savings in wood costs to make a rough assessment of holopulp economics.

The active chemicals used in kraft pulping are NaOH and Na_2S. Typical values of the chemical requirements are 12% alkali as Na_2O and 20% sulfidity for hardwoods, and 16% Na_2O at sulfidities of 25-30% for softwoods. At pulp yields of 50%, this translates to about 450 lb. NaOH and 110 lb. Na_2S for hardwoods and 520 lb. NaOH and 220 lb. Na_2S for softwoods. At market prices, these chemical costs would be up in the $15 to $20 per ton area. However, the kraft recovery system lowers these costs significantly. Using the data in Progress Report Eighteen (4), it appears that unit costs of 1 cent/lb. for Na_2S and 2 cents/lb. for NaOH are not unreasonable. Then the cost of these chemicals for kraft would range from about $10-$13 per ADT. If a bleached kraft pulp is to be considered, additional chemical consumptions might include up to 6% Cl_2, 4% NaOH, and 1% ClO_2 on the pulp. At prevailing market prices, this could add another $8-$10 per ADT.

The steam required is estimated at about 4000 lb./ADT pulp for batch digesters and about 2000 lb./ADT for continuous digesters. For bleached kraft, these would run somewhat higher. It appears that steam costs would run about $1-$4/ADT pulp. There are no significant power costs in the kraft system besides the pumps, etc.

The total costs for chemicals and utilities for kraft is about $14/ADT for unbleached, and $22/ADT for bleached. This may be compared with the $28/ADT for holopulp. The difference is the same order as the potential savings in wood costs. Thus, a rough analysis indicates comparable economics. However, this comparison is very sensitive to the effects of recovery on chemical costs. In order to obtain a more definitive comparison of costs, a more detailed cost estimate is needed.

SECOND APPROACH

The second approach to estimating relative costs for chemicals and utilities between processes necessitates a detailed listing of requirements within the process steps. This gives a more accurate estimate of these costs. Chemical costs are significantly different from the first approach since capital costs of recovery are not assessed against the chemicals and the utilities in the recovery area are considered separately.

The cost items which are considered in this analysis are as follows:

a. chemical make-up
b. other chemical requirements
c. electrical power
d. steam
e. other utilities.

These are estimated both for holopulp and for kraft as a reference process and relative costs compared. Appropriate leverage factors for these costs are identified.

Make-Up Chemical

Since holopulping involves sequential treatments with chlorine-based oxidants and caustic, it is necessary to have two sources of make-up chemical to have control over both sodium and chlorine inventories. Sodium chloride would be the prime make-up chemical in the amount required to satisfy the element in lesser demand. Depending on the loss pattern, additional make-up of Cl_2 (or HCl) or caustic (or Na_2CO_3) would be needed to achieve a balance. Make-up requirements are not expected to be high. About 30 lb. of NaCl and 10 lb. of Cl_2 or NaOH per ton of pulp should be sufficient. This assumes a high washing efficiency which would be required anyway because of the highly colored nature of the effluent. If recovery is 90%, losses should not exceed 50 lb. of NaCl and 20 lb. of Cl_2 or NaOH per ADT. Using costs of 1.4 cents/lb. for NaCl and 4 cents/lb. for Cl_2 or NaOH, make-up costs could range from about \$0.80 to \$1.50 per ton of pulp.

Chemical make-up for kraft is generally saltcake (Na_2SO_4) and has tended to run about 100 lb. per ton of pulp. At current market prices of $28/ton, this would amount to $1.40/ton pulp. However, the efforts to close up kraft mills to reduce sulfur emissions has affected this requirement. The net effect has been and will be a reduction in the total make-up required and a partial shift to sulfur-free make-up (NaOH or Na_2CO_3). Since these sulfur-free make-up chemicals tend to be more costly than saltcake, the effects may balance each other so that the sodium make-up cost would remain about $1-$2/ton pulp. In addition to the sodium make-up, make-up lime is also needed. This may run about 20-30 lb./ton pulp which at a cost of about 1 cent/lb. means lime costs of 20 cents-30 cents/ton pulp. The total chemical make-up cost for kraft should be around $2/ADT.

Other Chemical Requirements

For holopulp, this would include chemicals (such as $BaCO_3$) for cleaning up the recovered salt, sodium dichromate to protect the chlorate cell electrodes, and asbestos for diaphragm cell replacement. These were estimated to be about $1/ton pulp in Report Eleven (3). If the recovery system includes a causticizing system, the cost of make-up lime would also have to be added. This would be about 10-20 cents/ton pulp. The total cost of "other" chemicals for holopulp should run about $1/ton pulp. If the holopulp was to be fully bleached and the bleaching process would only involve Cl_2, ClO_2 and NaOH, there would be no separate charge for bleaching chemicals, since the bleach could be looked at as a multistage extension of the pulping process.

For the kraft process, there would be no other chemical charges on the unbleached pulp. However, there would be substantial chemical requirements for the bleached kraft, since all of the bleaching chemicals would be purchased. In the case of a CEDED system, this might amount to 120-180 lb. Cl_2, 60 to 100 lb. NaOH, and 15-30 lb. ClO_2 per ton of pulp. At prevailing prices, these chemicals could cost from $8 to $15 per ton of bleached pulp. Thus, an estimate of $10/ton for bleaching chemicals is not unreasonable.

Electrical Power

The major elements in this category are the power requirements for the electrolytic cells and the fiberizing step in the holopulping process. It is recognized that there are other power requirements for pumps, mixers, etc., but it is felt that these are relatively small and of similar magnitude for both processes. On this differential basis, it is assumed that the power required for kraft is negligible, and that the only power requirements which have to be considered for holopulp are for fiberizing and the electrolytic cells.

The power required for the chlor-alkali cells is expected to range from 2600 to 3000 kw.-hr. per ton Cl_2. This is equivalent to 0.8 to 0.9 kw.-hr. per lb. of NaCl electrolyzed. All NaCl which passes through the recovery system and is not simply recycled to the pulping system must be electrolyzed. The power required for chlorate cells is related to the demand for ClO_2. For a given chlorate cell and ClO_2 generator efficiency there is a fixed power requirement per lb. of ClO_2. In Report Eighteen (4), this was estimated at about 5 to 6 kw.-hr. per lb. ClO_2 produced. The power required for fiberizing was estimated earlier in this report at about 130 kw.-hr./ton pulp.

The power required for chlor-alkali cells is dependent on the recovery system configuration. The following cases may be considered:

1. The recovered chemical is converted entirely to NaCl by adding HCl to either the spent liquor or the Na_2CO_3 formed. In this situation, all of the NaOH used in pulping (and bleaching) is derived electrolytically, and the NaOH consumption is the controlling factor in chlor-alkali power requirements.
2. The liquor contains excess chlorine, and the recovered chemicals are NaCl and HCl. The HCl could be concentrated and used in the ClO_2 generator. The NaCl would be electrolyzed and all NaOH would be electrolytically generated. Thus, NaOH consumption would be the controlling factor in this case too.
3. The recovered chemical would be mainly Na_2CO_3 with some NaCl. This would be causticized and then concentrated to drop the NaCl out which would then be electrolyzed. In this case, the power for chlor-alkali would be determined by the sum of the chlorine used as ClO_2 and Cl_2 in pulping (and bleaching).

<u>Thus, if causticizing is employed, Cl_2 production is the controlling factor, otherwise, NaOH production is.</u>

The total power required for holopulp is then:

Fiberizing: 130 kw.-hr./ADT pulp

Chlor-Alkali Cells: 1.2 to 1.35 kw.-hr./lb. NaOH used (no causticizing) or
1.3 to 1.5 kw.-hr./lb. Cl as Cl_2 or ClO_2 (with causticizing)

Chlorate Cells: 5 to 6 kw.-hr./lb. ClO_2 produced.

The actual requirements would depend on specific cases, but the following estimates are reasonable: 200 lb. ClO_2 and 270 lb. NaOH per ton of pulp. Then the power required would come to:

Fiberizing:	130 kw.-hr.
Chlor-Alkali:	340 kw.-hr.
Chlorate:	1100 kw.-hr.
	1570 kw.-hr./ADT pulp

This is the biggest single cost item for holopulp for which there is no analogous cost for kraft. Depending on local power rates, the cost of power on a differential basis is likely to run from $12 to $20 per ADT, with a likely value of about $15.

Steam

Steam is required for evaporating the spent liquor and for heating reaction vessels up to the desired temperature. These needs are similar for both processes, but the relative amounts required differ. In addition, a certain amount of steam is generated by incineration of the liquor which must also be taken into account. These factors must be analyzed for each process:

"digester" steaming requirements,
bleach tower steaming requirements,
fiberizing,
liquor evaporating steam,
other evaporation requirements, and
steam generation.

The amount of steam required to heat the "digesters" is dependent on many variables: the temperatures to be reached, consistency, availability of hot water, and the degree of heat conservation practiced. It will also be somewhat dependent on the number of stages employed. The amount of steam required for this operation for holopulp was estimated at 1300 lb. steam/ADT pulp in Report Eleven (3). This was for a three-stage process. Increasing the number of stages could tend to increase this value, while better heat economy could decrease it somewhat. A good part of this total is for heating the ClO_2 solution, which must be chilled initially, and is thus fairly unavoidable. The estimate of 1300 lb. steam per ton for heating appears reasonable for holopulp. Direct steaming requirements are higher for the kraft process because of the significantly higher cooking temperature. These have been estimated at around 4000 lb./ADT pulp for batch digesters and about 2000 lb./ADT for continuous digester.

The amount of steam required for bleaching will depend on the number of stages, amount of ClO_2 used, temperatures, etc. It is possible that the holopulp may be easier to bleach, requiring only a DED sequence. For a conventional CEDED sequence for kraft, steam requirements can range from 1200 to 5700 lb./ton pulp depending on the availability of hot water. It would appear that as a first rough estimate, bleach plant steam requirements could be taken at 2000 lb./ton for holopulp and 3000 lb./ton for kraft.

Fiberizing is a step used only in the holopulp process. Steam requirements have been estimated at 500 lb./ADT pulp.

Steam required for concentrating the waste liquor is dependent on the amount of liquor solids per ton of pulp, weak liquor concentration, final liquor concentration and steam economy. For holopulp at 65% yield, there would be about 1600 lb. of liquor solids per ton of pulp. This liquor would be obtained at relatively low solids content, probably from 5 to 8%. The water evaporated per ton is given by:

$$\text{Water evaporated} = S_L\left(\frac{1}{C_i} - \frac{1}{C_f}\right) \qquad (9)$$

where: S_L = total liquor solids, lb./ADT pulp

C_i = initial liquor concentration, lb. solid/lb. liquor

C_f = final liquor concentration, lb. solid/lb. liquor.

At a total solids of 1600 lb./ADT and an initial solids of 7%, the water evaporated to reach 50% solids is 19,700 lb. This can be compared with a typical evaporation requirement of 14,000 lb. for the kraft process based on 3000 lb. solids per ton and a concentration of 15% solids. The holopulp liquor requires more evaporation, although the difference is not as much as it would seem from the solids content alone. This is due to the high yield nature of holopulp and the consequent decrease in liquor solids per ton. Assuming a steam economy of 4.5, the steam requirement is 4400 lb./ton for holopulp and 3100 lb./ton for kraft. The holopulp evaporation requirement is very sensitive to the initial solids content of the holopulp liquor. If it could be raised to 10% solids, the holopulp evaporation requirement would be less than kraft. This would be very difficult to achieve because of the multistage nature of the holopulping process, the relatively low solubility of ClO_2 in water, and the need for efficient washing.

In the holopulp system, steam is also required for evaporating caustic solutions. This requirement will exist regardless of whether or not causticizing is practiced in the recovery system. In the "all electrolytic" recovery system, the caustic solution from the diaphragm cells would be concentrated to drop out most of the salt for recycle. The evaporation load would depend on the amount of caustic produced and the degree of salt removal desired. This evaporation requirement was estimated in Report Eleven (3) at about 1300 lb. H_2O evaporated per ton of pulp. If the system using causticizing with lime is employed, the white liquor after causticizing will have to be concentrated to drop out the salt. The amount of evaporation will depend on the amounts of NaOH and NaCl present and the degree of salt removal desired. Based on the data of Reeve and Rapson, this evaporation requirement would be about 6 lb. H_2O per lb. NaOH, or as much as 2500 lb. H_2O. Caustic evaporation would be carried out in a limited number of effects and so at a relatively low steam economy. Using a steam economy of two, the steam required for caustic evaporation would run about 600 to 1000 lb. per ADT pulp.

Another steam requirement in the holopulp process is that used in the ClO_2 generator. Based on information furnished by Chemech, this would be about 3.7 lb. steam/lb. ClO_2, or about 800 to 1000 lb./ADT pulp. A bleached kraft mill could have a requirement of this type too, but the amount of ClO_2 used is not very great and it is simplest to lump it in with the cost of the ClO_2 for the bleached kraft case.

A final steam requirement for the holopulp process is that required for chilling the absorber water for the ClO_2 plant. The ClO_2 is produced as a solution containing 8 to 10 g./liter with water chilled to 50°F. or less. Based on information furnished by Chemech, this should amount to about 4 to 5 lb. steam per lb. of ClO_2 produced, which would tend to be about 900 to 1100 lb. steam per ADT pulp. The relatively small amount needed for a bleached kraft mill can be included with the cost of the ClO_2.

Both processes have the ability to generate some steam from the heat released upon incineration of the spent liquor. The amount so generated will be dependent upon the amount of liquor solids, the heating value of the liquor, and the heat recovery efficiency. For the kraft case, a typical value is 3000 lb. solids/ton pulp and a heating value of 6600 Btu/lb. solids so that the total heat available is 19,800,000 Btu/ton pulp. Often 55-58% of this heat input can be recovered as steam, or as much as 11 to 11.5 million Btu's. If a value of 1200 Btu per lb. of steam is assumed, the steam generation from the kraft furnace may run about 9000 lb./ADT pulp. On the other hand, with holopulp, there would be about 1600 lb. liquor solids per ton of pulp with a heating value of about 5500 Btu/lb. solids. Thus, the total heat available would be 8,800,000 Btu/ton pulp, and with a recovery efficiency of 60-63% (no reduction would be needed), about 4500 lb. steam/ADT pulp could be generated.

A summary of the total steam requirements for holopulp and kraft is shown in Table I.

Utilities other than steam and electrical power can be ignored, since the steam requirement for the ClO_2 absorber water chiller has already been included.

<u>Summary</u>

A summary of the cost estimates for chemicals and utilities for holopulp and kraft is shown in Table II. These estimates are approximate only and should not be taken as unchangeable or applicable to all cases. On a comparative basis, the costs for chemicals and utilities for an unbleached holopulp are $15 to $25 per ton higher than for an unbleached kraft. The difference is much less for the bleached pulps. In this case, the holopulp costs are only $9 to

$13 higher than the corresponding costs for bleached kraft. This is approaching the potential savings in wood costs due to higher yields. This would indicate that holopulp should be more competitive for bleached grades.

TABLE I

SUMMARY OF STEAM REQUIREMENTS

	Holopulp, lb./ADT	Kraft, lb./ADT
Digester heating	1300	2000[a]-4000[b]
Bleach plant heating	2000	3000
Chip fiberizing	500	
Spent liquor evaporation	4400	3100
Caustic evaporation	600-1000	
ClO_2 generator	800-1000	
Absorber water chiller	900-1100	
Total, unbleached	8500-9300	5100[a]-7100[b]
Total, bleached	10,500-11,300	8100[a]-10,000[b]
Steam generated	4500	9000
Deficiency, unbleached	about 4000	
Deficiency, bleached	about 6000	
Surplus, unbleached		about 2000-4000
Surplus, bleached		-1000 to +1000

[a]Continuous digester.
[b]Batch digester.

TABLE II

SUMMARY OF CHEMICAL AND UTILITY COSTS

	Holopulp, $/ADT	Kraft, $/ADT
Unbleached Pulps		
Chemical make-up	$0.80-$1.50	$2.00
Other chemical requirements	$1.00	--
Electric power	$12.00-$20.00	--
Steam deficiency	$2.00-$4.00	-($1.00-$2.00)[a]
Unbleached totals	$15.80-$26.50	$0.00-$1.00
Bleached Pulps		
Chemical make-up	$1.00	$2.00
Other chemical requirements	$1.00	$8.00-$15.00
Electric power	$14.00-$22.00	--
Steam deficiency	$3.00-$6.00	$\approx$ $0.00
Bleached totals	$19.00-$30.00	$10.00-$17.00

[a]Surplus exists, thus a cost credit.

The high costs of electrical power and steam for holopulp clearly show it to be a high energy consuming process. The electrical demand is a consequence of using chlorine compounds in general and ClO_2 in particular as pulping reagents. The steam demand is mainly a consequence of the higher pulping yield and weaker spent liquor. These costs have a profound impact on the economics of holopulping. The availability of low cost steam and electrical power is practically a requirement for the economic success of the process.

CAPITAL REQUIREMENTS

The amount of capital needed is an important aspect of the total economic picture and is included in this analysis. Again, emphasis is directed at differences in the capital costs for holopulp and for the reference pulp, kraft. Differences in capital costs arise in several different ways:

1. The equipment needed for the two processes is similar, but differs in size.
2. One process may require a particular piece of equipment which is not needed by the other.
3. Different kinds of equipment may be used to satisfy similar operational needs.

Examples of all three of these types abound in the comparison between holopulp and kraft. The woodyard and the evaporators are two areas where size is the major factor. The refiners for chip fiberization and the electrolytic chlor-alkali and chlorate plants are examples of equipment needed solely for holo-pulp. High pressure batch or continuous kraft digesters <u>versus</u> the sequence of vessels (and washers) for holopulp is an example of the third type.

The capital requirements for the holopulp plant will be partially dependent on the process configuration. Two cases will be considered:

1. A conventional recovery furnace burning liquor to give a high carbonate smelt, causticizing the green liquor, evaporation of the white liquor to drop salt, and electrolytic processing of the salt.
2. A fluidized bed furnace burning liquor to produce $NaCl$ and a little HCl, and full electrolysis.

The following elements would be included in the capital cost analysis.

Holopulp		Kraft
wood preparation		wood preparation
chip fiberization refiners		
pulping vessels		digesters
pulp washers		pulp washers
liquor evaporator		liquor evaporator
recovery furnace	fluid bed furnace	recovery furnace
causticizer	HCl scrubber	causticizer
calciner		calciner
caustic evaporator		
chlor-alkali cells		
ClO_2 plant		ClO_2 generator
bleach vessels and washers		bleach vessels and washers

The wood preparation facilities would be smaller for holopulp because of the higher pulp yield. It is anticipated that the facilities would be the same except for size. Relative costs would depend on the cost for kraft, the scale exponent and pulp yield. Assuming a holopulp yield of 65%, a kraft yield of 50% and a scale factor of 0.6, the capital cost for wood preparation facilities would be 15% less than the cost for kraft. If wood preparation facilities are assumed to cost $3 million for a 500 tpd kraft mill, the savings in capital costs for holopulp would be about $0.5 million.

Chip fiberization would require the use of pressurized double-disk refiners of the type used in making dry process fiber for particle board. The cost of these is estimated to be about $250,000 to $300,000 for a unit capable of processing 150 tpd of wood. For a pulp production of 500 tpd, 5 units would be needed at 65% yield. This would cost about $1.25 to $1.5 million based on the above estimate.

The equipment needed for carrying out the holopulping reactions is expected to be very similar to that used in conventional bleach plants, i.e., reaction towers, interstage washers and the necessary transfer equipment. Sizes of the vessels were estimated in Report Eleven (1). The ClO_2 stages were estimated to be about twice the size of the bleach towers for a comparable tonnage. Alkaline extraction towers are expected to be about the same size as for a bleach plant. The washers would be expected to be about the same as for a bleach plant unless the drainage characteristics of the holopulp would force larger washers. The number of stages to produce unbleached holopulp would probably be fewer than are now used to bleach kraft pulp. Current available estimates of the capital cost for a 500 tpd conventional five-stage bleach plant range from $5 to $7 million. Taking these data and the above factors into account, it appears that the capital cost for the pulping and washing equipment for holopulp should not exceed $5 million. For comparative purposes, the cost for a continuous digester and washing equipment for kraft at comparable tonnages is estimated at about $5 to $6 million. Thus, there appear to be potential capital savings of up to $1 million for holopulp in pulping and washing steps. It appears doubtful if greater savings can be obtained. Washing needs for holopulp could obliterate any savings of capital in this area. The need to recycle liquors and use maximum water conservation in order to maintain acceptable solids contents in the spent liquor could lead to much more expensive washing systems.

The costs for evaporators is expected to be dependent mainly on the amount of evaporation needed. The evaporation requirement for holopulp is estimated to run about 40% greater than kraft. If the 0.6 rule holds, the capital costs would be about 22% greater. If it is assumed that the kraft evaporators cost about $1 million, then the increased capital cost for holopulp would be about $200,000. Two factors could seriously change this picture. If the chlorides (and relatively low pH) in the holopulp liquor lead to high corrosion rates, then more expensive materials of construction could be required. The experience of kraft mills having chloride in the liquor suggests this <u>may</u> not be a problem. A second potential problem is some tendency of intermediate pH holopulp liquors to have a very high viscosity above about 40% solids. This could require the use of more expensive, forced circulation evaporators.

The recovery furnace is one item where holopulp is expected to show savings in capital costs compared to kraft. This should occur regardless of the type of incineration used in holopulping. If a conventional recovery furnace is used, the holopulp should require a smaller furnace because of the lower Btu input. The holopulp Btu rating may be only 45% that of the kraft. Using this ratio, and a scale exponent for recovery furnaces of 0.51 as discussed in Report Eighteen (<u>4</u>), the capital cost of the holopulp furnace would be only 2/3 the cost of the kraft. Since the kraft furnace would cost on the order of $7.5 million, the expected savings for holopulp are about $2.5 million. It is unlikely that comparable savings would exist with the precipitator, since the lower tonnage would be offset by the probable greater dust loadings. Comparable savings should be obtainable with a fluidized bed — waste heat boiler incineration system with associated HCl scrubber.

The causticizing-calcining system would be sized according to the amount of caustic produced. In a kraft process, this would run around 500 lb. NaOH per ton of pulp. In a holopulp process, the NaOH formed by causticizing would likely be about 300 lb. per ton (when causticizing is used at all). Assuming a scale factor of 0.6, the cost for the causticizing-calcining system would be about 75% of the cost for the kraft process. Assuming $3 million as the capital cost for causticizing-calcining for a 500 tpd kraft mill, the savings for holopulp in this area would be about $0.75 million.

A caustic evaporator is required in the holopulp process to drop salt out of the caustic solutions. The cost of this evaporator must be estimated for the case in which causticizing is employed. The cost of the caustic evaporator in the chlor-alkali plant is included in that overall plant cost. It appears that about 2000 lb. of water would be evaporated in processing about 300 lb. of NaOH. The cost of the system to accomplish this is estimated to be about $0.5 million.

The chlor-alkali plant is a cost item only for the holopulp process. For a 500 tpd holopulp plant using the "all electrolytic" recovery approach, a chlor-alkali plant of about 75 tpd of Cl_2 would be required. Capital costs for such a plant were estimated at about $6.5 million in Report Eighteen (4). In the system with causticizing, much less salt would have to be electrolyzed. The size of plant needed would be about 25 tpd of Cl_2, and the capital required would be about $3.5 million.

The chlorine dioxide plant is another item which tends to be unique for holopulp, although a relatively small ClO_2 generator would be needed for a kraft bleach plant. At a total ClO_2 usage of 9% on the wood, a ClO_2 plant of

60 tpd capacity would be needed. Based on the data reported in Report Eighteen (4), the capital cost of this plant would be about $7 million. At 6% ClO_2 total consumption, a 40 tpd plant would be adequate and would cost about $5 million.

One final item to include in the capital estimates is the cost of bleach plants for the two cases. The cost of a conventional five-stage bleach plant for 500 tpd kraft was estimated earlier at from $5 to $7 million. The cost of a bleach plant for holopulp could be considerably lower because of a need for fewer stages and because a ClO_2 generator would not have to be included. Costs for a holopulp bleach plant might be expected to run about $3 to $4 million, with potential savings of about $2.5 million for the holopulp process.

A summary of this differential comparison of capital costs is given in Table III. It is evident that holopulp is a higher capital cost process than kraft. The excess capital would range from about $5 to $7 million for a 500 tpd plant. The increased capital requirement for holopulp lies almost entirely in the cost of the chlor-alkali and ClO_2 plants. Thus, it is a consequence of using chlorine-based chemicals in general, and ClO_2 in particular, as pulping chemicals.

Table III gives capital cost savings or deficits for the holopulping process relative to kraft in millions of dollars for 500 tpd plants.

LABOR COSTS

Labor requirements are not expected to be greatly different between the two processes and so there will be relatively little difference in labor costs. In estimating labor needs, it is convenient to divide the plant up into the

TABLE III

SUMMARY OF DIFFERENTIAL CAPITAL COSTS

	$, MM	
	Savings	Deficit
Wood preparation facilities	0.5	
Chip fiberization		1.25
Pulping and washing equipment	1.0	
Spent liquor evaporator		0.25
Recovery furnace	2.5	
Causticizing-calcining	0.75-3.0[a]	
Caustic evaporator		0.5-
Chlor-alkali plant		3.5-6.5[a]
ClO_2 plant		6.0
Unbleached Net		6.75-7.0[a]
Bleach plant	2.5	
Bleached Net		4.5

[a]No causticizing in holopulp system.

following areas: woodyard, pulping, evaporation and burning, chemical regeneration, and bleaching. At comparable tonnages, it is difficult to see that there should be significant differences in labor for pulping, bleaching, evaporation and burning, since the processes do not differ that much. One possible exception is that more corrosive conditions in the holopulp process could require more maintenance labor. It is possible that less labor would be required in the holopulp woodyard, because less wood would have to be handled. However, if the operation is reasonably well automated, there should be little difference. The area where there could be labor differences could be in chemical regeneration.

Chemech (4) has estimated the labor requirement for running a 50 tpd ClO_2 plant and an 80 tpd Cl_2 plant at 35 man-days of operating labor and 2 man-days of supervisory labor. The labor required for the white liquor manufacture for a kraft mill would be about 6 man-days of operating labor and 1 of supervisory labor. The difference is 29 man-days of operating labor and one of supervisory labor per 500 tpd of pulp. Assuming $40/man-day for operating labor and $80/man-day for supervisory labor, this would amount to about $2.50 per ton of pulp.

BY-PRODUCTS

The only by-products of major economic significance are turpentine and tall oil. These are mainlv recovered from the kraft pulping of certain softwoods. Holopulping, on the other hand, especially for bleached grades, is much more suitable for hardwoods. In the work with softwoods, an alkaline pretreatment is used and it has been assumed that the materials can be recovered from liquors before oxidative treatments. This could require separate liquor handling. As far as this analysis is concerned, the following assumptions are made:

1. With hardwoods, the value of potential by-products is negligible for both cases.
2. With softwoods, the turpentine can be recovered from fiberizer relief condensate and tall oil from the pretreatment liquor.

The net effect of these two assumptions is to drop by-products out of the economic analysis. This certainly gives holopulp the benefit of the doubt. The possibility of generating by-products from the hemicellulose content of the pulp is also ignored in this analysis.

PRODUCTION COST SUMMARY

The total production cost picture for holopulp relative to kraft can be summarized as follows:

Wood costs	\$10/ADT less
Chemical and utility costs	\$14 to \$20/ADT more
Labor costs	\$2/ADT more
Total operating costs	\$6 to \$12/ADT more
Capital requirements	\$9000 to \$14,000/daily ton more

It is important to note that <u>both</u> the capital and operating costs are higher for holopulp than for kraft. There is no doubt that holopulp is a more expensive pulping process than kraft. In general, the additional costs for energy and equipment are not completely recovered by savings in wood costs. These increased costs are a direct consequence of the use of chlorine-based oxidants such as ClO_2 as pulping reagents. These materials do not lend themselves to simple recovery and thus expensive, power consuming, chlor-alkali and chlorate cells are required. The big economic disadvantage of these electrolytic steps is that they require both high capital outlays and large amounts of electrical power. This is another way of restating the fact mentioned earlier in this report; ClO_2 at 10 to 12 cents per lb. is an expensive chemical to use in amounts ranging from 150 to 300 lb. per ton of pulp.

SPECIFIC EXAMPLES

The preceding analysis has been concerned with the general problem of holopulp economics vis a vis kraft. It is helpful to consider two special cases for a more specific comparison.

1. Fully bleached hardwood pulp.

2. High-yield semichemical softwood pulp.

Bleached Hardwood Holopulp

A procedure for making a bleached holopulp from red maple was described in Report Sixteen (5). The pulping step itself produced a pulp at a yield of 63 to 65% at a Kappa number of about 20. This pulp was then subsequently bleached.

The pulping took place in three stages as follows:

Alkali Conditioning — 3% NaOH, 10% consistency, 70°C., 15 minutes

Oxidation — 7.5% ClO_2, 1.33% Cl_2, 8% consistency, 25→35°C., 110 minutes

Alkali Extraction — 7.5% NaOH, 15% consistency, 80°C., 120 minutes.

The following bleaching sequence was used:

Stage I — 0.77% ClO_2, 0.38% Cl_2, 10% consistency, 60°C., 60 minutes

Stage II — 1.2% NaOH, 15% consistency, 70°C., 90 minutes

Stage III — 0.4% ClO_2, 10% consistency, 70°C., 60 minutes

The bleached pulp was obtained at a yield of 57-59% and a TAPPI brightness of 88.

Translating all of these data onto the basis of original wood and using 58% as the final yield gives the following amounts of chemicals employed per ADT bleached pulp:

ClO_2:	255 lb.
Cl_2:	50 lb.
NaOH:	350 lb.

The proportions of sodium and chlorine are such that incineration of the liquor would give 305 lb. of NaCl and 190 lb. Na_2CO_3/ton pulp. These levels are such that the most likely recovery configuration would involve HCl addition to the liquor and fluid bed incineration. This would then involve [illegible] lb. of liquor solids and 510 lb. NaCl produced/ton pulp.

The following items would be relevant to the costs in this system for 500 tpd plant:

Evaporation:	22,000 lb. H_2O evap./ton
Incineration:	10,000,000 Btu/ton pulp
Chlor-Alkali:	350 lb. NaOH/ton, [illegible] tpd Cl_2
ClO_2:	255 lb./ton, 64 tpd ClO_2

The cost estimates relative to a bleached kraft are as follows:

Wood: Holopulp yield 53%, kraft yield [illegible]

Kraft wood costs = $[illegible]/ton assumed

Savings = $8.25 per ton

Chemicals and Utilities

Pulping Chemicals:	Even trade with kraft		
Bleaching Chemicals:	Kraft costs $5 more		
Electric Power:	Fiberizing	—	150 kw.-hr.
	Chlor-Alkali	—	455 kw.-hr.
	Chlorate	—	1300 kw.-hr.
			1905 kw.-hr. at 8 mil = $15.25

Steam:	Digester and bleach plant net	—	2000 lb. Kraft
	Fiberizing	—	500 Holo
	Liquor evaporation	—	1800 Holo
	Caustic evaporation	—	600 Holo
	ClO_2 generator	—	950 Holo
	Absorber chiller	—	1100 Holo
	balance	—	2950 Holo
	Generated	—	4000 lb. more for Kraft
	Net Required:	—	7000 more for Holopulp
	at 75 cents/1000 lb.	—	$5.25 against Holopulp

Sum: 15.25 + 5.25 - 5 = — $15.50 more for Holopulp

Labor: $2.50 more for holopulp

Total Operating Cost Differential: $9.75/ton more for the holopulp

Capital Costs	\$, MM for 500 tpd Holopulp	
	Savings	Deficit
Wood prepn.	0.5	
Chip fiberization		1.5
Pulping washing	1.0	
Bleach plant	1.5	
Evaporator		0.25
Recovery furnace	2.0	
Caustic evaporator		0.5
Chlor-alkali		6.5
ClO_2 plant		7.0
Causticizing	3.0	
Net		7.75

This comparison of the economics of producing a bleached hardwood pulp by both holopulping and kraft shows the holopulp operating costs (excluding capital) are about $10/ADT higher and the capital needed is about $15,000/daily ton higher.

Unbleached Semichemical Softwood

Complete delignification of softwoods to produce bleached holopulps does not look economically attractive because of the much greater amounts of chlorine dioxide required. However, it is feasible to make very high-yield unbleached pulps which require some mechanical treatment for fiber liberation. These have been studied (5), and would seem to have properties such that they could be considered for board grades. An analysis of the economics of such a pulp compared with high-yield kraft will be made.

The following conditions were selected for this example:

Alkali pretreatment:	7% NaOH taken up on chips
Chip fiberization:	75 p.s.i.g. steam, 2.5 min.
Oxidation:	6.3% ClO_2, 25-35°C., 60 min.
Alkali extraction:	8% NaOH, 90°C., 60 min.
Mechanical defibration:	

Pulp Yield = 76%

The chemical consumption: ClO_2 = 150 lb./ton

NaOH = 356 lb./ton

Liquor: 1000 lb. solids/ton, 5% solids, 5000 Btu/lb. solids

Ash: 130 lb. NaCl, 355 lb. Na_2CO_3

Recovery configuration: Causticize recovered Na_2CO_3

Concentrate to drop NaCl

Electrolyze NaCl

Sizes:		
	Evaporation	— 18,000 lb. H_2O evap./ton pulp
	Incineration	— 5,000,000 Btu/ton pulp
	Causticizing	— 260 lb. NaOH/ton
	Chlor-Alkali	— 20 ton/day for 500 tpd pulp
	ClO_2	— 37.5 ton/day for 500 tpd pulp

The economic analysis of this case is as follows:

Wood costs: Holopulp yield = 76%, High-yield kraft = 55%

Kraft wood costs \$50/ADT

$$\text{Savings} = 50\left(1 - \frac{55}{76}\right) = \$13.80/\text{ton pulp}$$

Chemicals: Assume trade off with kraft

Electrical Power: Fiberizing — Assume trade off with kraft

Chlor-Alkali — 115 kw.-hr.

Chlorate — 825 kw.-hr.

940 kw.-hr. at 8 mil. = \$7.50

Steam:

Operation	lb./ton	Holopulp	Kraft
Fiberizing		700	
Digester heating		2000	2000
Liquor evaporation		4000	2700
Caustic evaporation		800	
ClO_2 generator		600	
Absorber water chiller		700	
	Sum	8800	4700
Generated		2500	7500

Net deficiency = 9000 lb. at 75¢/1000 lb. = \$6.70

Labor: Estimate holopulp requires \$1.50/ton more

Total Operating Cost Differential: 13.80 - 7.50 - 6.70 - 1.50 =

\$1.90/ton more for holopulp.

Capital:	Excess Costs, $, MM for 500 TPD	
	Holopulp	Kraft
Wood prepn.		0.5
Fiberization	0.5	
Pulping and washing		1.0
Evaporator	0.25	
Recovery furnace		3.0
Causticizer-calciner		0.75
Caustic evaporator	0.5	
Chlor-alkali	3.0	
ClO_2 plant	4.5	
Net excess cost	$3.5 million	

Thus, for this high-yield softwood pulp, the net operating costs (excluding capital) are about $2/ADT pulp higher for holopulp, and the capital costs are about $7000/annual ton higher. The economics of this case are more favorable than for the bleached hardwood holopulp. This is due to the greater yield difference, the use of less ClO_2, and the ability to use the recovery mode which employs causticizing.

DISCUSSION OF PRODUCTION ECONOMICS

The preceding general analysis, as well as the analyses for the two specific cases, has clearly shown the major features of holopulp economics. It is appropriate to summarize these findings and arrive at some basic conclusions regarding holopulp production costs.

The major economic plus factor in holopulp production is the savings in wood costs due to higher yield. These savings are quite significant and can be traded off against some of the adverse cost factors. In the holopulping process, the increased yield is obtained by selective delignification using chlorine-based oxidants. These chlorine chemicals are expensive and are responsible for increased capital and operating costs in the holopulping process. Thus, process economics turn on a balance between savings in wood costs and the increased production costs associated with the use of chlorine dioxide and chlorine. This is a very simple way of looking at holopulp economics. It is also quite valid.

Reduced wood cost is the only area where holopulp shows a clear economic advantage. These savings must be discounted somewhat by the loss in the Btu value of the wood which is conserved. Depending on the prevailing costs for fuel and for wood, this loss in fuel value could amount to from ... to 1/3 of the total savings in wood costs. Other areas in the process do not show a clear advantage for holopulp. It is unlikely that holopulping would show a significantly lower capital cost compared with kraft in the digester area, even though holopulp reactions are carried out at atmospheric pressure. The multistage nature of the holopulping process and the necessary washers and pulp handling equipment would tend to obviate that advantage. When the cost of the necessary refiners needed for chip fiberization is included, an even trade-off is about the best that can be obtained. Holopulp does show a significant capital cost advantage for the recovery furnace. However, this is mainly a reflection of the decreased amount of combustible material per ton of holopulp, and not due to a lower cost technology. In any event, the savings ...

capital costs at the recovery furnace are overwhelmed by the costs of the chlor-alkali and ClO_2 plants. It also appears that there are no major savings to be obtained at the bleach plant, since multistage systems of comparable complexity are needed for both holopulp and kraft. Holopulp would have the advantage of economy of scale on the bleach plant chemical costs.

Holopulp is a high energy consuming pulping process compared with kraft. There is a very significant electrical power requirement for this process, on the order of 1000 to 2000 kw.-hr. per ton of pulp more than for kraft. Thus, a 500 TPD holopulp plant could require as much as 40 megawatts of power. In this day and age of rising energy costs and actual shortages of electrical power, this is a serious disadvantage. There is also a general Btu shortage in the process (which appears in this analysis as a steam deficiency). This would have to be obtained from purchased fuels, which could also be a serious drawback under present circumstances. The long-range economic outlook for the process turns on the relative costs of wood <u>versus</u> energy. At the present time, these conditions are unfavorable to holopulp.

A comment should be made regarding the economic analysis of the very high-yield unbleached softwood pulp. Although this analysis indicated that production and capital costs were reasonably close between holopulp and kraft, there were several assumptions made. Most importantly, it was assumed that a holopulp could be made at 75% yield which had properties equivalent to a high-yield kraft at 55% yield. This difference in yield is very significant, because it is the source of the positive input in the economic equation. A <u>very</u> substantial yield difference must exist for good economics. A second assumption was an equivalence in recovery of turpentine and tall oil between the two processes. A third assumption was that the low amount of liquor solids per ton and the additional process steps involved would not give an unacceptably dilute spent liquor. These assumptions must be borne in mind in interpreting these cost estimates.

In summary, holopulp production economics hinge on a trade-off between savings in wood costs due to higher yield and increased utility and capital costs due to the use of chlorine dioxide and chlorine as pulping chemicals. Using current estimates, the savings in wood costs alone cannot justify the higher costs involved, and holopulp would be more expensive to produce than kraft. Holopulp is a heavy energy consuming process (relative to kraft) both for fuel and electrical power. This is a distinct disadvantage in a developing energy crisis.

ANALYSIS OF PAPERMAKING COSTS

The preceding section analyzed the cost of producing holopulp. Since pulp is an intermediate product whose value depends on the paper made from it, and pulps with a whole range of properties can be produced, consideration only of pulp costs is incomplete. It is necessary to consider the economic implications of the papermaking properties as well. This is the purpose of this section.

There are several ways in which cost savings in papermaking can be achieved:

1. The pulp may be easier to refine. This could lead to savings in the capital cost of refiners and for the power needed for the refiners.
2. The use of a pulp of special properties could lead to a lower overall cost for the total papermaking furnish. This could be achieved in a number of ways.
    - A. Increased proportion of low cost fiber such as groundwood or recycled fiber.
    - B. Increased proportion of lower cost filler materials such as clays.
    - C. Decreased amounts of expensive additives.
3. The runnability of the pulp could be such that it would increase the production capacity of the paper machine.
4. The particular properties of the pulp could be such that it would generate a higher return per unit weight of paper made. This could fit into one of two categories.
    - A. It might be possible to meet specifications with a lower basis weight sheet. This would generate increased sheet area per ton of paper.

B. The improved strength, (or other properties) could be such that it would permit a premium price.

Each of these items has its negative counterpart as well, and a comparison with a reference pulp is needed for the economic analysis. Kraft is the reference pulp chosen.

COST OF REFINING

Because of the relatively high hemicellulose content of the holopulps, they tend to be easy beating pulps. They hydrate very readily and rapidly develop bonding and strength properties. Data published in the literature (6) indicates that the rate of beating for holopulps is three to four times faster than the rate for a corresponding kraft pulp. Since the time required to beat a pulp is directly proportional to the energy required to beat that pulp, holopulps could consume only 1/3 to 1/4 the energy required to beat a kraft pulp. The power required to beat kraft pulps can range up to 30 hp. days/ton, so the savings in power requirements could run up to 20 hp. days/ton or about 360 kw.-hr./ton pulp processed. Using the previous estimate of 8 mil. power, this becomes about $3/ADT saving for holopulp.

The ease of beating of holopulp is not an unmixed blessing. If the pulp beats too easily, it will tend to refine while subjected to normal pulp handling procedures. Thus, it could be carried past the desired degree of beating. Control of the beating process is also more critical and more difficult if the pulp hydrates very easily. In some of the laboratory studies which have been carried out, the beating time for the holopulp was zero. This could be an indication of potential trouble. Under these conditions, the ease of refining could become a handicap.

TOTAL FURNISH COSTS

The complete furnish for any particular grade of paper often consists of a mixture of several different substances. In such instances, the inclusion of a more expensive component, such as holopulp, could possibly be justified if it also permitted greater use of a lower cost material. The controlling factor would be the overall cost for the entire furnish.

One situation where this possibility could arise is in the use of blends. An example could be a groundwood-kraft blend in which consideration is given to replacing the kraft with holopulp. Another possibility would be the use of a blend of holopulp and a groundwood or recycled fiber as a replacement for kraft. These cases can be analyzed quantitatively. The savings in the cost of a furnish using holopulp compared to an old blend not using holopulp is given by:

$$\text{Savings} = (F'_O - F_O)\ (C_R - C_O) - F'_H\ (C_H - C_R) \qquad (10)$$

where:

$\underline{F'_O}$ = Fraction of material "other" than holopulp or reference pulp in new blend.

$\underline{F_O}$ = Fraction of "other" material in old blend.

$\underline{C_R}$ = Cost of reference pulp, \$/ADT.

$\underline{C_O}$ = Cost of "other" material, \$/ADT.

$\underline{F'_H}$ = Fraction of holopulp in new blend.

$\underline{C_H}$ = Cost of holopulp, \$/ADT.

The fraction of holopulp which can be used and show an economic advantage is given by:

$$F'_H \leq (F'_O - F_O)\ \frac{(C_R - C_O)}{(C_H - C_R)}. \qquad (11)$$

Thus, the amount of holopulp which can be used must be equal to or less than the increase in the fraction of "other" material, weighted by the ratio of the difference in cost of other material and reference pulp to the difference in cost between holopulp and the reference pulp.

The following example may be considered. A furnish now consists of 30% kraft and 70% groundwood. If holopulp is substituted for kraft, what must be the minimum % groundwood in the new furnish? Assuming a $50/ton difference in cost between the groundwood and kraft and $15/ton between holopulp and kraft, it is found that the new furnish could contain up to 23% holopulp and would require no less than 77% groundwood. Using the same relative cost figures in considering replacing 100% kraft with a holopulp-groundwood mixture, shows that a mixture of 77% holopulp and 23% groundwood is economically equivalent to the kraft pulp.

Because of the high hemicellulose content of holopulp which tends to develop extensive bonding capability, it appears that potential exists for savings of this type. However, the experimental work needed to demonstrate the papermaking equivalence has not been carried out, and savings of this type remain a conjecture at present.

Similar considerations hold for the use of fillers, provided that the cost of the fillers is less than the costs of the pulps. This is the case with clays. Data reported in Report Sixteen (5) showed that bleached maple holopulp gave slightly better retention of Huber SSW Filler Clay (87% to 77%) than the corresponding bleached kraft pulp. Also reported were handsheet data for sheets filled with clay. The specific scattering coefficient was 10 to 20% higher for the kraft pulp at all loading levels. Strength properties, such as breaking length and tensile stiffness were slightly greater for the holopulp. At the same scattering coefficient, the holopulp sheet contained more clay, and the strength properties were similar. However, the kraft sheet was able to absorb equivalent amounts of filler at some sacrifice in strength properties but improvement in opacity. Since these tests compared unbeaten holopulp at 215 C.F. with a kraft pulp beaten to 350 C.F., the effects of additional beating of the kraft pulp should also be considered. It is likely that this would tend to bring the pulps into line.

Equation (11) can be used to estimate the increase in the total amount of filler in the furnish needed to justify the use of holopulp. The ratio of cost differences from the reference pulp is represented by $\underline{R} = \dfrac{\underline{C}_R - \underline{C}_O}{\underline{C}_H - \underline{C}_R}$. Substituting $1 - \underline{F}'_O = \underline{F}'_H$ in Equation (11) and rearranging gives:

$$F'_O - F_O \geq \frac{1 - F_O}{1 + R} . \qquad (12)$$

Clays will cost about \$20/ton, so the difference in cost between kraft and the clay may be about \$100/ton. Assuming holopulp costs \$15/ton more than kraft gives $\underline{R} = 6.67$, and at a \$10/ton difference, $\underline{R} = 10$. If the reference loading value is 10% ($\underline{F}_O = 0.1$), then the filler retained would have to go up to 21.7% at \$15/ton cost difference and up to 19% at \$10/ton cost difference. Clearly, a very significant difference in filler capacity is required if the economics of using a more expensive pulp is to be justified on this grounds.

Although the potential to achieve some improvement in the overall cost picture through increased amounts of low-cost filler in the furnish exists, this has not yet been substantiated by actual data. An increase in clay retention by about 10% on the sheet is needed to reclaim a cost difference of

\$10 to \$15 per ton of pulp between holopulp and kraft. This would be a very substantial increase if it could be brought about. Titanium dioxide may be another matter. It is about 3 times as expensive as either pulp, and the more TiO_2 needed, the poorer the economics. Preliminary tests showed little difference in the retention efficiency of TiO_2 between holopulp and kraft. However, the holopulp did require larger amounts of TiO_2 to reach the same levels of specific scattering coefficient. If this is a general pattern, the result is unfavorable to holopulp economics. The data are subject to the same uncertainties as the clay data discussed above, and so are inconclusive.

PRODUCTION CAPACITY

A significant economic advantage could be obtained if holopulp would permit higher machine speeds which would increase paper machine productivity. This would be especially true for a mill in which the machines were running at capacity. An increase in machine productivity would reduce capital and labor charges per ton of paper. It appears that the value of increased production would be very dependent on the individual mill situation.

It has been fashionable to think of holopulps as very gelatinous, slow stocks which would be difficult to run on a paper machine. According to this school of thought, holopulp would likely require slowing the machine down and thus the productivity factor would work against holopulp economics. <u>This is not necessarily true</u>. Tests of a bleached maple holopulp and a bleached maple kraft on the IPC web former indicated that the holopulp was slightly easier to run. In particular, the formation of the holopulp sheet was better and it tended to dry more readily. Although the web former is by no means a paper machine, these results would seem to indicate that expected papermaking problems may be highly overrated. The published literature also supports this. It has been reported (6) that the ease of refining, coupled with the more rapid drainage, higher wet web strength and ease of drying which was observed, all indicate the ability to increase paper production relative to that obtainable with conventional pulp.

It would be premature to draw any conclusions regarding the effect of holopulp on paper production rates at this time. Extensive testing on a much larger scale would be required to determine if production benefits can be obtained and to what extent. However, it is possible to conclude that major runnability differences might exist, and they would not necessarily act against holopulp.

PROPERTY DIFFERENCES

The physical properties of holopulps would, in general, be different from conventional pulps, and these would affect sheet properties and hence the economics. In order to do a rigorous analysis of the economic implications of property differences, it is necessary to assign a cost factor for each difference in properties which is significant. This is because properties are functions of the degree of beating, and the many different properties do not respond in the same way. The type of grade under consideration would have a strong effect on the cost factors. Individual mill situations would also be important. The information needed to carry out such a rigorous analysis is not available, so more approximate methods will be used.

Many of the ultimate uses of paper are dependent on sheet area, and so the basis weight of the sheet becomes important. If a sheet is made at a common basis weight from holopulp and from conventional pulp, there will be fewer fibers in the holopulp sheet because the increased yield is obtained through increased weight of the individual fibers. This had led to questions concerning the ability of the holopulp sheet to meet strength requirements at a common basis weight. The results of comparative handsheet tests seem to indicate that bleached hardwood holopulps can achieve comparable properties to bleached hardwood kraft pulps at a common basis weight. Thus, it appears that the basis weight of the holopulp sheet would not have to be increased to meet property criteria. It is unlikely that it could be decreased either. Thus, there would be little economic impact from this source. One potential problem could be with optical properties such as opacity. The holopulp sheets tend to be of higher density and lower opacity. It is possible that basis weights would have to be increased for this reason with the associated economic penalty for less sheet area per ton.

The main impact of properties would seem to be one of requiring certain values to meet specifications. As a general rule, once specifications are met, improvements in certain properties do not generate an increased price for the product. Thus, the main concern of properties would be the ability to meet the specifications for certain grades. Handsheet data indicate this should be possible for bleached hardwood pulps although there might be problems with opacity. Data on unbleached softwoods is less conclusive. The burden of proof would seem to be with holopulp on this point. It seems unlikely that property considerations would act as a major economic benefit to holopulp, and they could be detrimental if specifications cannot be met.

PAPERMAKING SUMMARY

The economic aspects of papermaking using holopulps has been examined. The only clear effect is the ease of beating of holopulps. If this can be controlled and does not result in overrefining the holopulp stock during handling operations, it could result in savings of $2 to $4 per ton. Other aspects of the papermaking problem such as increased use of lower cost materials and runnability on the paper machine could significantly influence the economics. However, the extent that such benefits could be obtained remains to be demonstrated. On the whole, <u>there is no firm evidence that economic advantages of holopulp in papermaking could justify a higher cost for the pulp itself</u>. On the other hand, there is no conclusive evidence for adverse economics either.

ENVIRONMENTAL COSTS

One final factor which must be considered in the economic analysis is the impact of environmental control legislation. This is one area where holopulp is considered to have some distinct advantages over the kraft process. The purpose of this section is to examine the air and water emission profiles for holopulp, compare these with the kraft process, and attempt to attach economic values to the differences. In making this comparison, new mills will be considered for each process, since existing mills are not very suitable for conversion to holopulp.

The biggest single advantage of the holopulp process is that it is a sulfur-free pulping process. Thus, it is not subject to the very malodorous reduced sulfur gases that are characteristics of the kraft process. Another major advantage is that the bleaching process is totally compatible with the pulping process (actually an extension thereof) so that complete recovery of the bleach effluent is quite practical. Among the disadvantages are a tendency for significant BOD loadings in condensates, possible low level HCl emissions, and the possibility of some NaCl particulate emissions. The following survey of emission sources for the holopulp process will attempt to identify the problem areas and to serve as a basis for comparison with kraft.

AIR EMISSIONS

The only significant air emission problem in the wood preparation area would be from the bark and waste burner. The magnitude of this source would be somewhat less than kraft because of the smaller amount of wood processed per ton of pulp.

In the cases where the fiberization step is carried out as a "dry process" (50 to 65% moisture on a wet basis), there could be a small dusting problem. There would also be a small amount of wood volatiles given off with the spent fiberizing steam. These could be condensed out if necessary. With softwoods, with or without a simultaneous or prealkaline treatment, turpentine should be flashed off with the vent steam. This could be recovered from the condensate. It is not expected that the noncondensable gases from this step would be odorous.

No serious emissions are expected from the pulping and washing operations (this holds for bleaching too). These operations are currently practiced in bleached kraft mills without any problems. As long as the ClO_2 is exhausted before leaving the reactor, there would be no significant odor and no hazard.

No serious air emission problems are expected from the spent liquor evaporator. A slight smell, somewhat reminiscent of burnt wood, has been observed during evaporation of holopulp liquors. This is not very strong and is not unpleasant. It is apparently due to some volatile organics. No significant emissions of chlorine compounds have been detected.

Some air emission problems may be associated with the incineration step. The type and extent of these emissions will depend on the incineration method used. When the conventional soda-type recovery furnace is used, with the high carbonate ash, there will be a significant particulate load (both Na_2CO_3 and NaCl) coming from the furnace. This would put a burden on the precipitators, but is certainly a manageable problem. There is no evidence to indicate that there would be any significant emissions of gaseous chlorine compounds. If fluid bed incineration is practiced, there is likely to be a slight concentration of hydrogen chloride in the off gases. This could be handled with a wet scrubber.

In the recovery configurations employing a causticizing and calcining system, there will be the dust problems associated with the lime kiln. The magnitude of this problem would be less than that for the kraft mill, because less caustic would be produced per ton of pulp.

No major problems are anticipated for the chlor-alkali system. Hydrogen would be vented or burned and trace chlorine contamination could lead to small HCl emissions which would have to be scrubbed. Noncondensable gases from the caustic evaporator should not be a problem. Some chlorine could be burnt with hydrogen to form HCl in a hydrochloric acid-forming system. There is a potential for HCl emissions from this source.

The chlorine dioxide generation system would also constitute no problem if proper precautions are used. Potential sources are the chlorine-containing off gases from the absorber which have to be burnt with hydrogen to form hydrochloric acid, and the disposal of the remaining hydrogen from the chlorate cells.

In general, the air emission picture for holopulp is quite good. The process should be substantially odorless. The most serious problems would seem to be possible small hydrogen chloride emissions from various sources, and the need to contain effectively the ClO_2 and chlorine. This favorable air emission situation should generate cost benefits compared to kraft.

The kraft mill, is faced with problems of TRS emissions and particulate emissions. There is also a potential problem with SO_2. The particulate problem would be of the same order of magnitude for holopulp and for kraft, although somewhat greater for kraft. There is no SO_2 emission problem in holopulp as there could be from the kraft recovery stack. However, emissions of SO_2 from auxiliary boilers could be more severe for holopulp because of the much greater need for process steam in the holopulp process. The kraft TRS emission problem has no counterpart in the holopulp process and, from the publics' viewpoint, is the major "pollution" problem of the pulp industry. The cost of TRS emission control was estimated as part of the NAPCA Study of Atmospheric Emissions in the Wood Pulping Industry and reported at the 1970 TAPPI Engineering Conference in Denver, Colorado (7). For a new mill, the total cost for controlling TRS emissions to less than 1 lb./ADT was estimated at $0.20/ADT. All of this cost was associated with control of the noncondensable gas emissions from the digesters and multiple-effect evaporators. It was assumed that, for a new mill, there would be no incremental cost for keeping TRS emissions below 0.5 lb./ADT in the recovery stack. These estimates seem to be rather low. They do reflect the fact that equipment and procedures for control of malodors are not that extensive when they are incorporated as part of the new installation. In the same report, it was estimated that the cost of improving an existing mill to meet the same standards was at about $1.60/ADT. Most of this additional cost was associated with the control of recovery stack emissions, although it was assumed that a new recovery furnace was not needed.

It appears that the net cost advantage to holopulp of eliminating TRS emissions would be about $1 to $2 per ton in a new mill. This is the tangible cost savings. Certain intangible factors would also have to be considered.

The kraft mill would still have an odor problem (although significantly lessened) and would continue to be subject to public pressures. Further reduction in reduced sulfur emissions below the levels used in the NAPCA study would get into technological gap areas and would likely be much more costly. The current procedures for eliminating TRS emissions from the recovery stack involves oxidizing them to SO_2. If the recovery stack is also subjected to very low limits on SO_2, the present technology would be pushed to its limits and could prove to be insufficient. Thus, while current conditions would give a relatively small economic advantage to holopulp on this point, the possibility exists that future developments could bring a major advantage.

AQUEOUS EFFLUENTS

The advantages of the holopulping process with respect to the aqueous environment are somewhat less evident than the air advantages. The following is a point-by-point comparison of holopulp effluents with kraft effluents.

In the woodyard, the technology for holopulp is essentially the same as kraft. Thus, there is not expected to be any significant difference in kind of effluents. The amount of effluent would be somewhat reduced for holopulp because less wood would need to be processed for the same amount of pulp.

The fiberization step is not considered to contribute significantly to the aqueous effluents. If the vent gases are condensed for recovery of turpentine, there would be a small amount of organic-containing condensate.

It is expected that there will be little discharge of effluents from the pulping and bleaching operation. The entire process hinges on the ability to carry out the sequential pulping and washing operations with a minimum amount of water so that the liquor is sufficiently concentrated for use in the recovery system. The bleach plant in a holopulp process is a direct continuation of the pulping process itself and virtually indistinguishable from it. The effluents from the pulping and bleaching steps would be of two types: the first would consist of leaks, spillages, and the like and should be contained and added back to the liquor system; the second would be the residual liquor in the pulp leaving the final washer stage. If the total liquor recovery system is 99% efficient, this would amount to about 20 lb./ADT of liquor solids discharged, about 1/2 of which would be organic.

There will be a definite problem with the condensates from liquor evaporation. Holopulp liquors tend to be significantly lower in pH than kraft liquors and more organic is distilled over into the condensates. In this respect, the evaporator condensate problem for holopulp is more akin to sulfite than kraft. Data given in Report Fifteen (8) indicated evaporator BOD_5 loads of about 50 lb./ton pulp could be expected.

If a conventional recovery furnace is used, there should be no significant effluent problems. If the fluidized bed system is used, a weak acid stream from an HCl scrubber may have to be handled. Several other sources of weak hydrochloric acid are possible in the chlor-alkali and ClO_2 systems. These are the only significant problems expected. Effluents from the causticizing-calcining system would be similar to kraft, but less per ton of pulp.

On balance, there are three major potential effluents from the holopulp mill. These are:

1. Evaporator condensates containing about 50 lb. BOD/ton,
2. Weak HCl streams containing perhaps [illegible] lb. HCl/ton pulp, and
3. Residual liquor, approximately 20 to [illegible] lb./ton pulp.

These may be compared with the effluents of a kraft pulp mill. Residual liquor losses might run about [illegible] lb./ton pulp, evaporator condensates about 10 lb. BOD/ton pulp, and the entire bleach effluent. The bleach effluent could contribute an additional 25 or more lb. BOD/ton pulp and a great deal of color. Thus, the aqueous effluents from the holopulp process are more severe than those from unbleached kraft. From a BOD standpoint, the holopulp mill and bleached kraft mill appear comparable. Color and inorganic loadings would be worse for the bleached kraft. The cost of effluent treatment at different levels was given in an article in Paper Trade Journal, October 2, [illegible] (9). The cost for 90% BOD removal (primary sedimentation followed by activated sludge, solids disposal by incineration) for an unbleached kraft and a bleached kraft was estimated at $5/ADT and $7.5/ADT, respectively. Comparing these figures to the potential effluents generated by holopulp would seem to indicate a $1-$2/ADT charge against holopulp compared with unbleached kraft and a $1-$2/ADT benefit compared to bleached kraft.

OTHER CONSIDERATIONS

One final factor to [illegible] in assessing the total environmental picture are the effects of a higher yield, higher utility consuming process. The higher yield represents greater pulp production for a given amount of wood. This could have a significant impact on forest resources. On the other hand, the high steam and power requirements represent a major demand for fuel and electrical energy in a time of growing shortage. At a requirement of 2000 kw.-hr.

per ton of pulp, a 500 tpd holopulp mill would consume power at a rate of 40,000 kilowatts. This could be a major power load on the suppliers. It is not obvious that the power supplies would be there to permit a substantial swing of pulp production from kraft to holopulp.

ENVIRONMENTAL SUMMARY

As far as the environmental situation is concerned, holopulp shows significant advantages in air emissions over the kraft process. This is particularly true with regard to odor. These advantages could result in savings of about $2/ton pulp for the holopulp process which could become much greater if odor restrictions get tighter. With regard to aqueous effluents, holopulp has a higher BOD loading than unbleached kraft and would compare favorably with a bleached kraft mill. These would result in a cost penalty of about $1 to $2/ADT compared to unbleached kraft and an advantage of $1 to $2/ADT compared to a bleached kraft mill. Thus, environmental costs could tend to break even for the unbleached case and show a $3 to $4/ton advantage for the bleached case.

Factors which are difficult to quantify could greatly influence this picture. It is difficult to assess all of the potential advantages of an odor-free sulfurless pulping process. On the other hand, the process demands relatively large amounts of fuel and electrical power. The availability of these items for large new ventures may be questionable.

GENERAL CONSIDERATIONS

This economic analysis has been concerned with the comparative economics between holopulp and kraft pulp. Basically, this turns on a balance between lower wood costs and environmental advantages, on one hand, and the use of more costly chemicals on the other. In general, holopulp is more costly to produce than kraft pulp because the yield increase achieved by selective delignification with ClO_2 cannot balance the high cost of this chemical. Analysis of specific cases indicated that a very high-yield softwood holopulp showed better economic potential than a bleached hardwood holopulp. This was due to a substantial yield increase achieved by not requiring full delignification, and by the use of less ClO_2. The bleached hardwood pulp, on the other hand, aimed at maximum yield by maintaining high delignification selectivity. It has not been established that this procedure is economically optimum. The purpose of this section is to examine that question in some detail.

The holopulping process may be considered to consist of sequential steps involving ClO_2 and NaOH. Since ClO_2 is the costly chemical, costs can be decreased by using less ClO_2. For a given degree of delignification, this would require a greater use of NaOH for lignin removal. Since NaOH is a less selective delignificant, the result would be a decrease in yield at a given lignin content. In examining this trade-off, it is useful to think of the process as occurring in two distinct steps:

1. A high-yield soda stage (alkaline treatment plus fiberization).
2. A selective delignification step (oxidation with ClO_2 plus alkaline extraction).

Relative rates of lignin and carbohydrate removal can be calculated for each of these steps, so that the composition of the final product can be estimated.

The following procedure is used in this analysis. It is assumed that the holopulp is produced by a single high-yield soda step followed by a single selective delignification step. For purposes of comparison, all pulps are considered to be brought to a common Kappa number (residual lignin content) by the selective delignification step. The independent variable is the extent of delignification in the soda stage. Once this is set, the extent of carbohydrate (nonlignin) removal in this soda stage can be determined. Then the ClO_2 required to reach the desired lignin level and the additional carbohydrate removal in the selective step can be determined. The results can be plotted as pulp yield vs. ClO_2 consumed at various levels of residual lignin. Although this model is admittedly crude, it does provide a means for examining the possibilities inherent in a ClO_2-NaOH pulping process.

Data on relative rates of lignin and carbohydrate removal in high-yield soda pulping are rather sparse in the literature. A limited amount of such data has been found. The data for aspen are shown in Fig. 8. These are used as indicative of hardwoods. Data on spruce and loblolly are presented in Fig. 9. These may be taken as representative of softwoods. Working curves, which are used in the subsequent analysis, are also shown on these figures.

The data for the selective delignification step can be obtained from the study of the delignification of red maple presented in Report Sixteen (5). These data show a strong relationship between the efficiency of the use of ClO_2 and the selectivity. These may be described by the ratios L/D = lignin removed/ ClO_2 used and C/L = carbohydrate removed/lignin removed. The following sets of values were found in the data on red maple delignification.

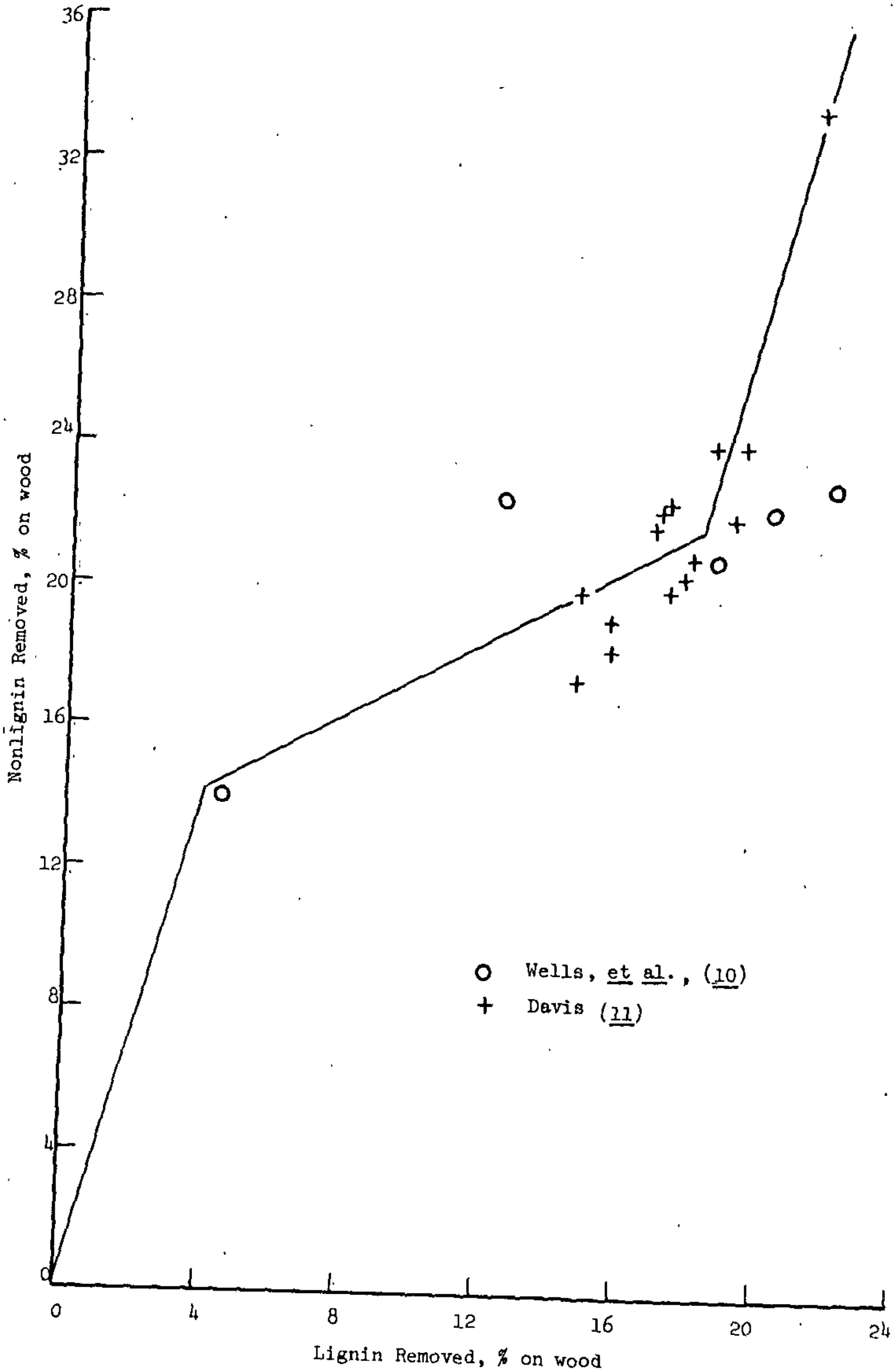

Figure 8. Lignin and Carbohydrate Removal in Soda Pulping of Hardwoods

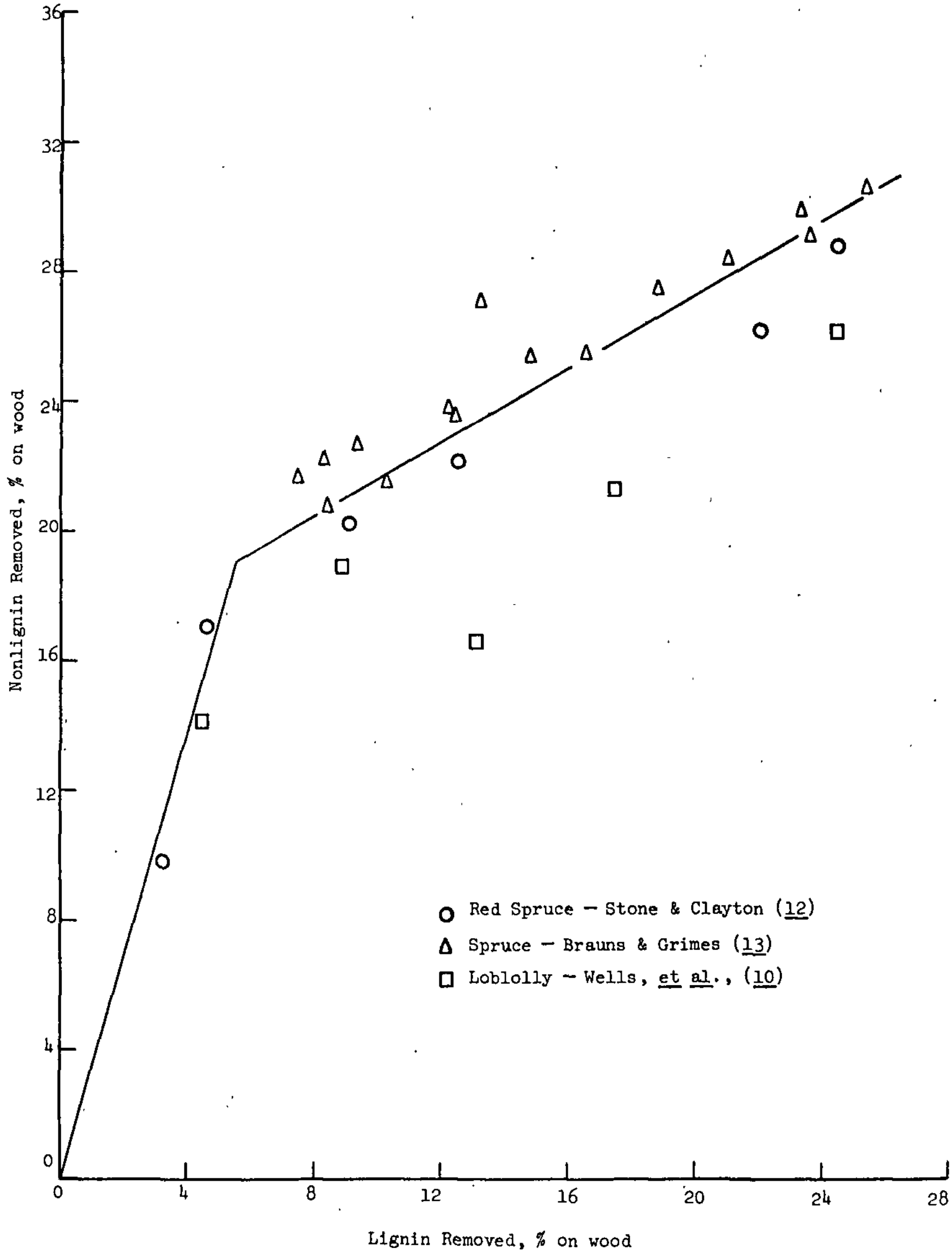

Figure 9. Lignin and Carbohydrate Removal in Soda Pulping of Softwoods

L/D	C/L
1.45	0.025
1.6	0.3
2.25	1.0

In this analysis, values of L/D = 2.0 and C/L = 0.75 will be used to describe the selective delignification step for hardwoods. The softwood data appear to be less clear cut, but it does appear reasonable to assume L/D = 1.75 and C/L = 0.3 for softwoods.

Calculated curves of pulp yield vs. ClO_2 consumption at residual lignins of 3% and 0% for hardwood are shown in Fig. 10. The crudity of the model must be born in mind in interpreting these curves; however, they do permit some insight into the general problem. The curves in Fig. 10 break into three distinct regions corresponding to the three parts of the soda "removal" curve shown in Fig. 8. At high levels of ClO_2 consumption (very little soda pretreatment), the yield falls very sharply with decreasing ClO_2 usage. This is because in the initial stages of soda pulping, carbohydrate is removed at a much greater rate than lignin. Thus, the replacement of a small amount of ClO_2 by soda carries with it a severe penalty in yield. In the middle region, the pulp yield does not change very much with ClO_2 consumption, indicating NaOH is as effective as ClO_2-alkali in delignifying in this region. (The model actually indicates NaOH to be a more effective delignifying agent in this area. This is because the model is oversimplified.) This rather surprising result is a consequence of the way the soda process attacks the carbohydrate and the lignin. Carbohydrate is removed first (corresponding to the rapidly falling portion of the curve) and then lignin. Once past the point where most of the readily extractable carbohydrate is removed, mainly lignin is

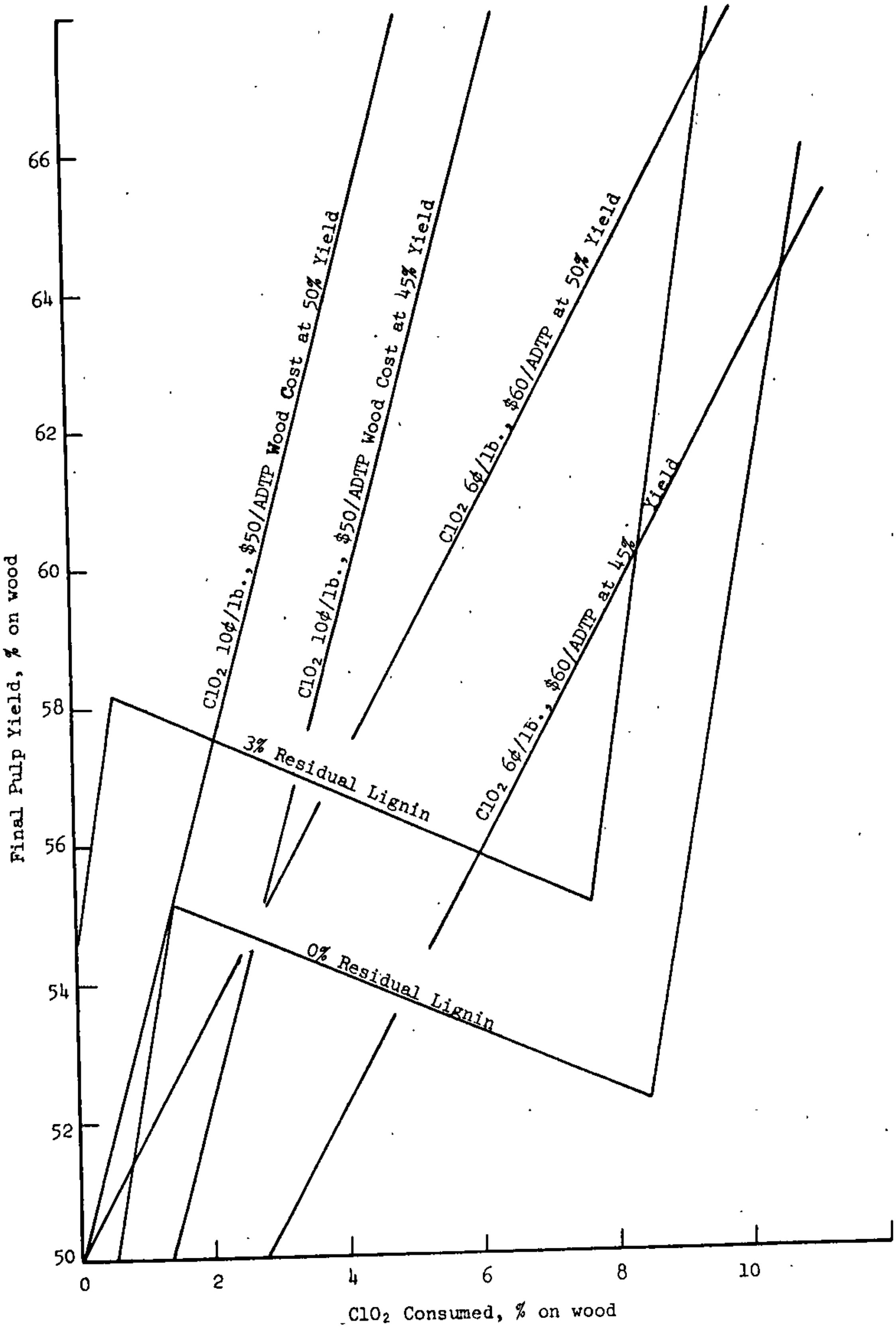

Figure 10. Pulp Yield vs. ClO_2 Consumption at Fixed Levels of Residual Lignin for Hardwoods

taken out. In this region, the soda is a fairly selective delignification agent on a differential basis. Thus, in this region, NaOH can be readily used to replace ClO_2 with little sacrifice in yield. (It must be remembered that to reach this region, it is necessary to lose a large amount of carbohydrate, and really high yields [above 60%] are not attainable.) If the soda treatment is carried too far, the yield again begins to drop sharply. This reflects the enhanced degradation of carbohydrate in attempting to get full delignification with caustic.

Figure 10 also has lines in which savings in wood costs are equated against ClO_2 costs for various values of ClO_2 unit cost, reference pulp yield, and wood costs for the reference pulp. Anything to the left or above these breakeven lines would indicate savings in wood costs that exceed ClO_2 costs. It would appear that there is a region with an extensive soda treatment giving pulp yields in the low to mid fifties which might be economically attractive. Further work to verify that such yields can be obtained and that pulp properties are satisfactory might well be justifiable.

Calculated curves for a softwood are shown in Fig. 11. It is clear that low lignin pulps cannot be made at yields in excess of 50% unless ClO_2 consumption of 12% or more are used. This demonstrates the general unsuitability of holopulping softwoods for bleached grades. The region being investigated for very high-yield semichemical pulps for board is shown on the figure. This clearly shows that these pulps have very high lignin levels. This is a totally different situation than exists with hardwoods. It would appear that such high lignin, very high-yield pulps are the only possible softwood pulps which would have any economic promise.

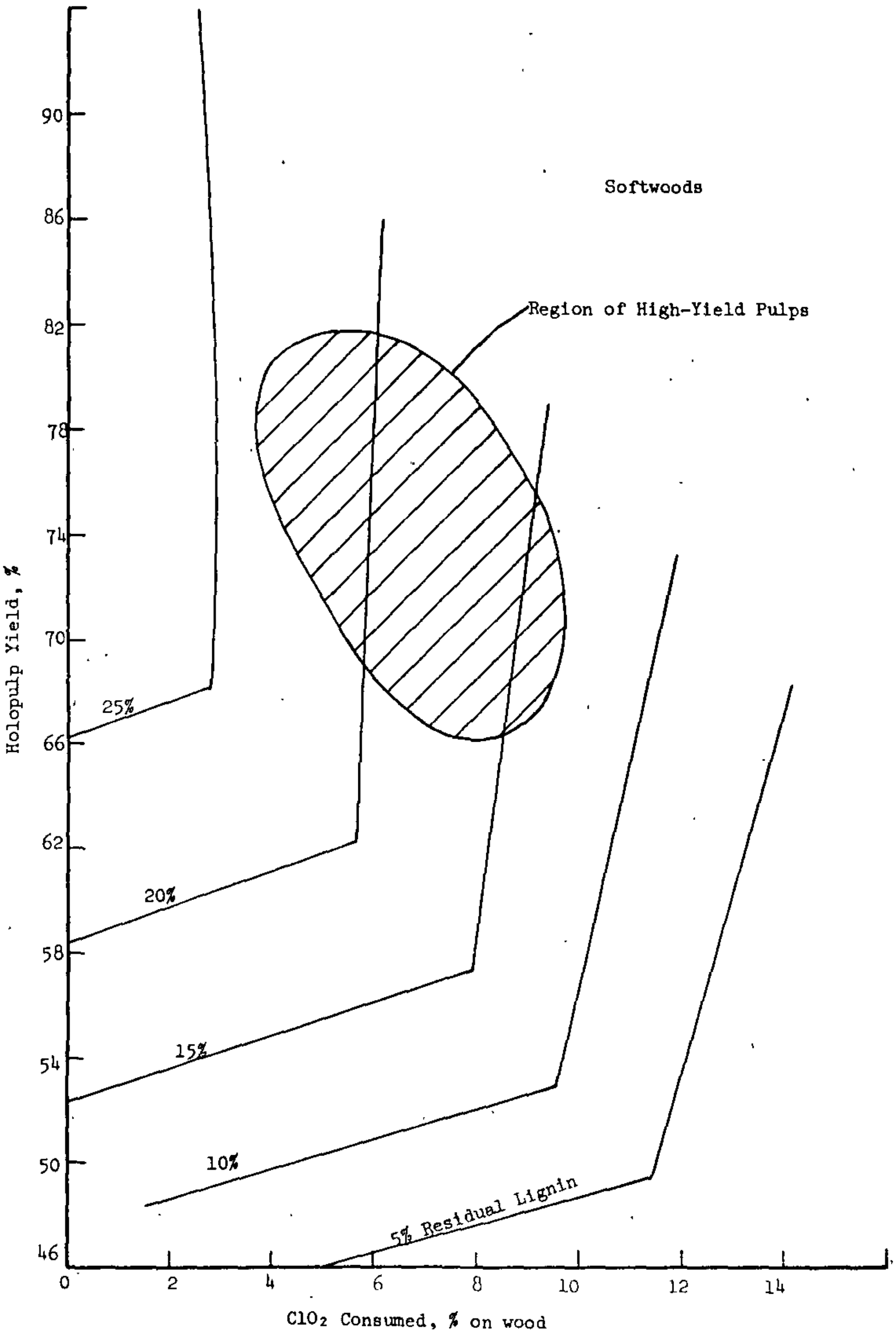

Figure 11. Pulp Yield vs. ClO_2 Consumption at Fixed Levels of Residual Lignin for Softwoods

This analysis shows that there is, in general, little to be gained in the yield-ClO_2 trade-off by substituting stronger alkaline treatments for ClO_2 consumption. This is because alkaline treatments (at least in the early stages of wood substance removal), tend to be antiselective, that is, they remove much more carbohydrate than lignin. What is needed is a relatively selective (and inexpensive) pretreatment which could remove a good bit of the lignin and not too much carbohydrate before using ClO_2. Of the common pulping treatments available, the one best meeting these criteria is neutral sulfite. This has not been given much consideration in this project because of the desire for a sulfur-free pulping system. The use of such a neutral sulfite pretreatment would require either a separate recovery system for the neutral sulfite portion, incineration and disposal of the combined effluents, or a rather complex incineration and salt purging in a concurrent kraft recovery plant. Despite recovery difficulties, the neutral sulfite pretreatment has some distinct advantages in chemical consumption. This is discussed in some detail in reference (6).

One final factor should be considered in examining the general problem. This is the question of the ability of the holopulp process to replace an existing process. It is obvious that the holopulp process is quite different from more conventional processes so that not all parts of an existing mill could be used. The question then turns to what parts of conventional processes could be used. If the holopulp process is one with NaCl the dominant recovered chemical, only the evaporators (if they could withstand the corrosion) and possibly the bleach plant (at a significantly lowered capacity if used as pulping vessels) would be salvagable. Of course, woodyard, fiber screening operations, etc., would remain the same. For the case of a sodium-dominated process, most of the kraft recovery process would be usable (evaporators, furnace, kiln and causticizing). It would be necessary to add a white liquor concentrator, chlor-alkali and ClO_2 plant, and pulping vessels and washers. Thus, the <u>conversion</u> of an existing mill to holopulp would involve capital expenditures on the order of $20,000 or more per daily ton. For relatively small tonnages of holopulp, it is possible to run a small holopulp plant beside a large kraft plant. The kraft recovery system could then be used to handle the holopulp effluent a la bleach effluent disposal schemes. This could be a relatively low capital cost approach, but tonnages would be limited and operating (chemicals) costs high.

ASSESSMENT OF HOLOPULP ECONOMICS

In the final analysis, the economics of holopulping are quite simple. They involve, essentially, a trade off between reduced wood costs due to higher pulp yields and reduced environmental costs due to the elimination of sulfur on one hand and increased chemical costs due to the use of chlorine oxidants on the other hand. On the basis of the analysis which has been carried out it must be concluded that this balance presently tips to the side of higher chemical costs. Holopulp is a more expensive pulping process than the kraft process. This is true with regard to both operating costs and capital requirements. The economic benefits of the higher yield and sulfur-free operation do not outweigh the costs due to the use of expensive chemicals.

The "expensiveness" of the holopulping process stems directly from the use of chlorine oxidants (ClO_2, Cl_2, or NaOCl) and is essentially innate in such systems. There are several reasons for this. Chlorine dioxide is generated from chlorate and chlorate must be produced electrolytically. Whether or not the chlorate is produced on or offsite is basically immaterial, since an electrolytic process is ultimately required. For this reason alone, there is a significant power requirement of about 5 to 6 kw.-hr. per lb. of ClO_2. Another factor influencing these costs is that all chlorine which enters the pulping step is ultimately converted to NaCl in the recovery plant. In order to regenerate the pulping chemicals this NaCl must be electrolyzed. This introduces another power requirement of about 1.4 kw.-hr. for each lb. of chlorine introduced into the pulping operation as either Cl_2 or ClO_2. These power requirements are essentially unavoidable in this process. The big economic disadvantage of these electrolytic steps is that they not only involve a substantial demand for electrical power, but they are also very expensive from a capital standpoint.

The costs of the necessary electrolytic processing, both for capital and for electrical power, are the major reason why holopulp is more expensive than kraft. These costs are so great that the miscellany of various savings around the rest of the system cannot counterbalance them.

Consideration was given to possible economic advantages in the paper-making area which might justify the use of a more expensive pulp. The only area in which such an advantage seemed readily apparent was in reduction in refining costs due to the ease of beating. By itself, this is not enough to cover the difference in pulp costs which were determined, and there is a potential problem of control of the degree of beating. Other areas such as improved machine runnability, use in blends, etc., were considered, but the data in these paper-making areas is too sparse to draw any conclusions. Any advantages that are present remain to be demonstrated.

The sulfur-free operation does give some tangible economic benefits from an air pollution control standpoint. Based on present estimates of costs to control air emissions for a new mill, these savings are nowhere near sufficient to justify the entire difference in production costs between holopulp and kraft. In addition, the holopulping process has some potential water pollution problems which could be more serious than those of the kraft process. Under these circumstances it is unlikely that the environmental control savings would render holopulping economical. The major unknown in this area is the possibility that the kraft odor problem would force emission restrictions beyond what is technologically possible. Under such circumstances major cost advantages for holopulp could be generated.

Much consideration has been given to possible changes in in-process variables which could have a large effect on the economics. These included the substitution of Cl_2 for ClO_2 and changes in recovery configuration such as the introduction of a separate causticizing operation. Although these had some effect on the economics, it tended to be small compared to the gap that exists between the cost of holopulp and that of conventional processes. <u>No major breakthrough in holopulp costs is likely to come through manipulation of in-process variables</u>. Only major changes in the pulping stoichiometry to reduce ClO_2 in particular and chlorine chemicals in general can result in a really significant drop in costs.

Calculations on a highly simplified model of the pulping operation indicate that greatly enhanced use of alkali to achieve a major reduction in ClO_2 consumption is unlikely to give desired results. The reason is that alkali is nonselective or even antiselective in that it attacks the carbohydrate material first. Thus, using large amounts of caustic to reduce ClO_2 demand will rapidly eliminate the yield advantage. There would seem to be two approaches to achieving a major cost breakthrough.

1. Produce pulps at high yields by incomplete delignification relying upon changes in character of the residual lignin and carbohydrate to obtain desirable pulp characteristics.
2. Employ another selective delignification agent which is either more efficient or less expensive than ClO_2 to remove the bulk of the lignin.

The first approach has been applied in the work on this project on high-yield softwood pulps. These appeared to be somewhat more promising economically than bleached hardwood holopulps, provided that the desired papermaking properties can be demonstrated. This approach would definitely be limited to unbleached grades.

The second approach has been used by Wilder (<u>6</u>) who employed a neutral sulfite pretreatment before selective delignification with ClO_2 and alkali. He was apparently able to make a fully bleached hardwood pulp at ClO_2 consumption less than 7%. However, the use of neutral sulfite could introduce some serious recovery problem which could wipe out any advantage.

Barring a major breakthrough in pulping technology, the future economic outlook for holopulp depends mainly on the relative costs of wood <u>versus</u> fuels and electrical energy, and the shape of environmental restrictions. Holopulp is, of course, favored by low cost energy and high wood costs. The present energy crisis does not bode well for it in the near future. The electrical power requirements for a 500 tpd holopulp plant are so vast (up to 40 megawatts) that availability may be a problem. One final consideration in this outlook is that present kraft mills could not be converted to holopulp without the capital expenditure of at least $20,000/daily ton holopulp.

NOMENCLATURE

$\underline{C}_{CW}$ = unit cost of clean wood, \$/ADT wood

$\underline{C}_D$ = unit cost of ClO_2, cents/lb.

$\underline{C}_f$ = liquor concentration leaving evaporator, lb. solid/lb. liquor

$\underline{C}_H$ = cost of holopulp, \$/ADT

$\underline{C}_i$ = liquor concentration entering evaporator

$\underline{C}_L$ = cost of labor for wood handling for reference pulp, \$/ADT pulp

$\underline{C}_O$ = cost of material other than holopulp or reference pulp in blend, \$/ADT material

$\underline{C}_R$ = cost of reference pulp, \$/ADT

$\underline{C}_U$ = cost of utilities used in wood preparation, \$/ADT wood

$\underline{C}_W$ = unit cost of raw wood, \$/ADT wood

$\underline{C}_{WR}$ = total wood cost for reference pulp, \$/ADT pulp

ΔC = $\underline{C}_{CWH} - \underline{C}_{CWR}$ = difference in unit cost of clean wood between holopulp and reference pulp, \$/ADT wood

C/L = ratio of carbohydrate removed to lignin removed

$\underline{F}'_H$ = fraction of holopulp in new blend

$\underline{F}_O$ = fraction of material "other" than holopulp or reference pulp in old blend

$\underline{F}'_O$ = fraction of "other" material in new blend

$\underline{f}$ = fraction of raw wood remaining after barking, chipping, and other processing steps

$\underline{H}$ = subscript designating holopulp

$\underline{I}_R$ = total capital investment in wood preparation facilities for reference pulp, \$

L/D = ratio of lignin removed to ClO_2 used

$\underline{n}$ = scale factor for wood-handling facilities

$\underline{n}_L$ = scale factor for labor

$\underline{P}$ = annual pulp production rate, tons

$\underline{R}$ = $(C_{\underline{R}}-C_{0})/(C_{\underline{H}}-C_{\underline{R}})$ = cost ratio

$\underline{R}$ = subscript designating reference pulp

$\underline{r}$ = annual charge factor against capital

$S_{\underline{D}}$ = ClO_2 consumed, % on wood

$S_{\underline{L}}$ = total liquor solids, lb./ADT pulp

$\underline{Y}$ = pulp yield, lb. pulp/lb. wood cooked

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THE INSTITUTE OF PAPER CHEMISTRY

T. M. Grace

T. M. Grace
Research Associate
Division of Materials
Engineering & Processes